Referee Report(s):

Referee: 1

This is a strong paper which addresses an important question regarding the role of RSPO certification for improving management of fire and fire-driven deforestation in permits for oil palm cultivation. The methods are clear, the report is well written and clearly organized, and the graphics are informative.

We appreciate the reviewer's recognition of the importance of our study on fire-driven deforestation in Southeast Asia and the role of RSPO certification.

I have the following questions/ comments for the authors:

1. Compliance benchmark date - The paper refers to 2009 as the year that RSPO began granting certification, and notes that forest loss and fire-driven deforestation declined after this date. However, the benchmark date used to determine compliance with RSPO criterion 7.3, after which new plantings should not replace primary forest or HCV areas, is November 2005. Why does the study use 2009 to assess compliance, given that RSPO uses an earlier year to assess compliance?

We agree with the reviewer that there are several important dates to consider regarding the evolution of RSPO and related criteria for certified plantations.

While the RSPO standard requires no replacement of primary forests or HCV areas after November 2005, the incentives to follow this requirement, and compliance with the requirement, have changed over time. The RSPO draft standard was piloted for two years (2005-2007) with volunteer oil palm companies who committed to avoid clearing primary intact forest and High Conservation Value (HCV) areas. Although this initial standard was approved in 2007, the first RSPO certificates for sustainable oil palm in Malaysia and Indonesia were not issued until 2008 and 2009, respectively. In 2010, the New Planting Procedure required that all member companies conduct an HCV assessment prior to clearing. In 2014, the Remediation and Compensation procedure recognized that RSPO members had cleared and planted after 2005 without first conducting an HCV assessment, and required companies to compensate for such clearance.

In a revised manuscript, we would clarify the evolution of the RSPO standard and additional requirements.

Specifically, we would discuss the sequence of events that precede certification in the Introduction, including company membership in RSPO and the agreement of all members to follow the Principles & Criteria, including Criterion 7.3:

"Companies interested in certification first become members of the RSPO and agree to the Principles & Criteria, including the prohibition on new plantings through deforestation of primary or HCV forests after Nov. 2005 without compensation (Criterion 7.3, RSPO 2013)."

In the methods, we propose to clarify the key dates for our evaluation of fire-driven deforestation and total fire activity: "Comparisons between certified (ever) and non-certified (never) plantations considered forest loss and fire activity over three time scales: 1) following the benchmark date for compliance with RSPO criterion 7.3 (Nov. 2005), 2) following the first issuance of RSPO certificates to Indonesian producers in 2009, and 3) following the date of certification for individual plantations."

In the results section, we propose to separately consider deforestation and fire activity during 2006-2009, 2009-2015, and the subset of all deforestation and fire activity on plantations with RSPO certification. For example:
"In Indonesia, annual rates of forest loss and fire-driven forest loss were higher in certified plantations before the first RSPO certificates were issued (2006-2008, 38,636 ha yr^{-1}) than during 2009-2015 (10,943 ha yr^{-1}). Between 2009 and 2012, the majority of forest loss and fire-driven forest loss occurred on plantations that had not yet received RSPO certification (Table B2), whereas plantations with certificates accounted for most forest losses identified in 2013-2014."

Due to the importance of being able to compare pre- and post- certification trends, I would find it useful to present the proportion of forest loss driven by fire each year in a table. It is difficult to see proportions in Figure 2 for years with low rates of forest loss, and Table 1 only provides this the aggregate proportion over the 2000 – 2014 period.
Breakdown by year would help illustrate whether, and when, certification alters fire use for forest conversion.

Below, we present annual forest loss and fire-driven forest loss for certified, non-certified, and buffer areas in Indonesia (Table B2) and certified plantations in Malaysia and Papua New Guinea (Table B3). In a revised manuscript, these tables could be presented online to complement the material in Figure 2 and Figure 4, or added to the main text for completeness. In addition, we have estimated the proportion of total forest loss and fire-driven forest loss on plantations following the receipt of RSPO certification, noting that the first RSPO certificates were issued to plantations in Indonesia in 2009 and in 2008 to plantations in Malaysia and Papua New Guinea. Table B4 provides a similar breakdown of total fire detections for certified plantations, including post-certification MODIS fire detections.

Table B2: Total and fire-driven forest loss for oil palm expansion in Indonesia from 2002-2014 within the certified and non-certified plantations.

Year	**Certified**				**Non-Certified**		**Buffer 5km**	
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Fire-driven loss (ha))	Total loss (ha)	Fire-driven loss (ha)
2002	12,646		4,961		86,179	21,890	184,140	29,713
2003	7,043		2,552		53,578	18,693	104,882	23,135
2004	32,885		12,587		158,904	62,232	288,634	71,538
2005	33,795		9,170		140,345	42,260	244,178	56,281
2006	54,313		12,023		224,249	85,081	320,690	88,869
2007	34,218		6,905		203,990	61,875	303,782	67,606
2008	27,376		876		252,538	31,337	355,449	47,793
2009	29,229	(1)	2,543	(0)	335,246	62,356	446,635	79,842
2010	6,267	(8)	306	(0)	120,598	14,330	228,111	28,634
2011	7,105	(23)	308	(42)	240,864	22,776	316,644	34,771
2012	9,163	(25)	495	(25)	334,453	45,787	512,886	80,585
2013	6,628	(50)	480	(82)	176,080	21,815	245,738	32,635
2014	7,264	(82)	774	(96)	195,885	31,298	302,012	48,848

Table B3: Total and fire-driven forest loss for oil palm expansion in certified plantations in Malaysia and Papua New Guinea during 2002-2014. All areas are given in hectares (ha).

Year	**Malaysia**				**Papua New Guinea**			
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)
2002	14,870		912		3,959		1,244	
2003	6,563		791		1,645		301	
2004	13,522		1,912		3,279		721	
2005	6,410		506		1,242		252	
2006	12,312		465		2,893		718	
2007	12,045		15		2,099		479	
2008	7,381	(2)	91	(0)	1,188	(34)	116	(7)
2009	15,467	(8)	69	(0)	938	(71)	3	(0)
2010	10,378	(19)	155	(8)	716	(85)	14	(96)
2011	8,222	(35)	120	(65)	1,065	(85)	4	(98)
2012	7,432	(48)	235	(63)	1,235	(79)	3	(77)
2013	3,261	(50)	85	(78)	756	(100)	0	(100)
2014	4,096	(82)	114	(81)	477	(100)	3	(100)

Table B4: Total MODIS fire detections for certified plantations, including post-certification fire detections.

	Indonesia		**Malaysia**		**Papua New Guinea**	
Year	Total fire detections	Post-Certification fire detections (%)	Total fire detections	Post-Certification fire detections (%)	Total fire detections	Post-Certification fire detections (%)
2001	169		124		37	
2002	1782		87		130	
2003	716		71		64	
2004	1821		87		130	
2005	1008		128		39	
2006	2712		17		83	
2007	197		12		61	
2008	87		9	(0)	43	(7)
2009	483	(0)	22	(0)	31	(0)
2010	72	(8)	18	(28)	44	(95)
2011	196	(29)	12	(50)	18	(67)
2012	191	(39)	21	(33)	44	(84)
2013	128	(55)	11	(55)	54	(100)
2014	361	(73)	35	(69)	52	(100)
2015	656	(100)	26	(100)	136	(100)

2. Buffer areas - The authors should articulate the purpose of the 5 km buffer area, and in particular clarify why they combine the buffer areas of certified and non-certified plantations. Given that the study assesses roughly 12 Mha of non-certified plantations, versus 1.5 Mha of

certified plantations, the trends in the combined buffer will largely reflect the characteristics of buffers around non-certified plantations and presumably more closely resemble the trends inside non-certified plantations. Combining the buffers masks potentially divergent trends in the buffer of the certified plantation management type, and obscures whether certification additionally impacts fire activity in areas surrounding the permit itself.

We appreciate the reviewer's suggestion to clarify our analysis of buffer areas surrounding oil palm plantations. Human ignitions are the dominant source of fire activity in Southeast Asia, and recent fire emergencies (e.g., 2013 and strong El Niño events in 1997-1998, 2002, 2006, and 2015) have intensified the debate over the source of fire ignitions. Two questions guided our inclusion of buffer areas surrounding plantations: 1) what is the role of smallholders adjacent to oil palm plantations for total fire activity observed from satellite sensors? 2) do buffer areas exhibit similar patterns of interannual variability in fire-driven forest clearing and fire detections as oil palm plantations? In other words, our main goal was to characterize fire and deforestation immediately surrounding oil palm plantations, not to contrast certified and non-certified buffers.

Buffer areas surrounding non-certified plantations cover a larger land area, as the reviewer correctly points out, but the patterns of remaining forested area and forest loss are similar for buffer areas surrounding certified and non-certified plantations (Figure R1). In addition, oil palm plantations in Southeast Asia are frequently adjacent to other oil palm plantations (Figure 1, see also response to Reviewer #3), meaning that it is difficult to attribute buffer activities to only certified or non-certified neighbors. As a result, we analyzed fire activity and forest loss for a single set of buffer areas surrounding certified and non-certified plantations. The 5km buffer was chosen based on expert judgment to capture the potential influence of forest loss and fire activity on the surrounding landscape, including the direct fire spread from adjacent lands into palm oil plantations, wind-blown embers from nearby fires, and the most acute impacts of smoke on both human health and ecosystems.

In the revised manuscript, we would clarify the characteristics of buffer landscapes in Section 2.1, including the fact that nearly 12% of the area within the 5km buffer was mapped as planted oil palm in 2010 (Gunarso et al., 2013; Carlson et al., 2013). Thus, the buffer region may reflect differences in management, in addition to differences in land use and land cover, based on the abundance of planted palm oil outside of large plantations.

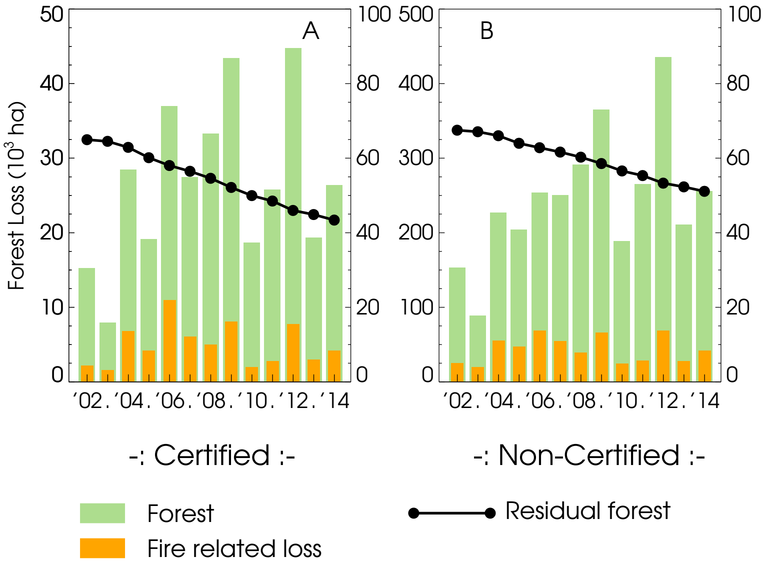

Figure R1: Forest (green) and fire-driven (orange) forest loss within the buffer (5km) areas of certified and non-certified oil palm plantation boundaries. Solid black lines indicate residual forest cover as a percentage of the buffer area adjacent to certified and non-certified plantations.

3. Underestimation of fire activity – The authors discuss limitations in satellite platforms, which detect fires, and suggest that these limitations may result in underestimation of fire activity. Is there any reason to think that this underestimation would bias the results, either by differentially underestimating fire density in time (e.g., after certification date), or in space (e.g., in certified concessions)?

The long-term record of Moderate Resolution Imaging Spectroradiometer (MODIS) active fire detections (MCD14ML) provides a consistent daily assessment of fire activity during the entire study period. MODIS detections therefore provide clear and consistent evidence for interannual (Figure 5) and monthly (Figure A3) variability in total fire detections in and around oil palm plantations. Limitations of MODIS fire detection from orbital coverage, cloud cover, or spatial resolution are also consistent over time, and are therefore unlikely to bias the analysis of fire activity in specific years or specific plantations.

The launch of additional satellite platforms, including the Visible and infrared Imaging Radiometer Suite (VIIRS) on the Suomi-National Polar orbiting Partnership (S-NPP) and Operational Land Imager (OLI) on Landsat-8, provide higher spatial resolution active fire information to detect smaller (or cooler) active fires and provide an unambiguous attribution of fire activity to specific land holders (see Figure 6). In the original manuscript, we highlighted the potential to improve operational satellite monitoring of fire activity using these new sensors, specifically to monitor land use change and environmental compliance. However, the benefits of new sensor systems do not diminish the value of long-term monitoring using MODIS. We propose to clarify the importance of the long and consistent MODIS data record in a revised manuscript:
"We used the time series of active fire detections from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites to evaluate the spatial and temporal patterns of daily fire activity during 2002-2015."

"The finer spatial resolution of these fire data capture additional details regarding fire activity that can be difficult to evaluate at MODIS resolution, including the precise location of active fire fronts, separation of flaming and smoldering fires (Elvidge et al., 2015), and detection of small and/or lower intensity fires (Schroeder et al., 2015)—an important component of fire activity in agricultural landscapes (Randerson et al., 2012)."

The potential for certification or other changes in land use and land management practices to alter the probability of detecting active fires from space is a separate issue from sensor performance. In our original manuscript, we specifically considered one aspect that could influence detection of fire-driven forest loss—changes in the size of clearings over time (Figure 3)—as smaller fires may be more difficult to detect using all satellite platforms. In addition to changes in clearing size, it is possible that land managers have altered the use of fires to avoid detection by burning during cloudy periods when detections are less likely or time intervals with less satellite coverage. New satellite sensors may partially address issues associated with smaller fires, but not with targeted burning to avoid detection. The potential management response to satellite monitoring capabilities is an interesting direction for further research, but a thorough evaluation of this issue is beyond the scope of this study. In a revised manuscript, we would recognize this line of research as a possible extension of this work using multiple sources of satellite-based fire detections.

4. Covariates of certification – The study could elaborate on the factors, which could cause different observed fire and fire driven forest loss trends between certified and non-certified plantations. The authors mention that companies preferentially certify older plantations that retain less forest cover. If this is the case, or if there are other characteristics which influence the placement of certified plantations or the outcomes with respect to forest loss and fire activity in certified plantations, then observed differences may not be the result of certification. The authors should clearly caveat the findings by acknowledging these covariates, and/or suggest what steps would be necessary to control for these in order to determine the causal impacts of certification.

We agree with the reviewer that a range of factors will influence fire-driven forest loss on oil palm plantations. In this study, we were primarily interested in the use of fire for forest conversion and interannual variability of fire detections in and around oil palm plantations. For these studies, the larger sample size of all certified and non-certified plantations fills an important data gap in our understanding carbon emissions from oil palm expansion—the degree of fire use during forest conversion. Companies and consumers purchasing palm oil are concerned about the amount of "embodied" emissions from forest loss and fire activity. Our study quantifies the amount of fire-driven forest loss embodied in certified palm oil based on a more inclusive look at the aggregate behavior among all certified oil palm plantations. As the reviewer points out, key aspects of the RSPO Principles & Criteria would be known to all RSPO members in the process of certifying plantations, including the Nov. 2005 benchmark date for deforestation of primary or HCV forest lands and the need to comply with environmental legislation banning fire activity.

Previous work that considered a broad range of matching criteria between certified and non-certified plantations was restricted to very small sample sizes (e.g., 4 plantations on peatlands in Cattau et al., 2016). In a separate study, we have more formally controlled for the diversity of plantation characteristics, including remaining forest cover, planted palm oil, age, and date of certification, among others (Carlson et al., under review). In a revised manuscript, we would specifically recognize that our results do not establish causality for differences between certified and non-certified plantations: For example:

"Following the start of RSPO certification in 2009, certified oil palm plantations in Indonesia had lower fire-driven deforestation and total fire activity during El Niño events than non-certified plantations. These reductions point to the potential for RSPO to contribute to REDD+ and to decrease fire ignitions during drought conditions, but our results do not provide conclusive evidence for a causal relationship between certification and lower fire activity."

5. Policy implications – The authors could further elaborate on the policy implications of their findings. They suggest that the benefits conferred by RSPO certification could be enhanced through expansion of certified plantations. How would this work? Given that certification is based on performance after the benchmark date, many plantations will poor past performance may not be eligible for certification (or would need to take advantage of a compensation mechanism). Would the expansion of the certified plantation portfolio therefore only apply to new plantations?

As the reviewer suggests, more widespread adoption of RSPO certification could be hindered by poor past performance because the barriers to entrance are likely to be high for a company that cleared after 2005 without an HCV assessment. However, entrance is not impossible due to the

2014 RSPO Remediation and Compensation Procedure that would allow certification of existing plantations in non-compliance with the 2005 cut-off date. Under this procedure, RSPO member companies that clear without an HCV assessment after 2014 are expelled from the RSPO, while non-member companies face steep costs to entrance. In the 2005-2014 period, companies face liability based on clearance date and membership status.

Given our findings that certified plantations in Indonesia had significantly lower fire-driven deforestation, even existing non-certified plantations with remaining forest could benefit from improved management practices associated with certification. However, even with full compliance with the RSPO Principles and Criteria, the overall environmental gains of certification may be limited, as the current Principles & Criteria do not restrict the clearance of all forests, only those designated as HCV or "primary."

Importantly, our study highlights how the RSPO Principles & Criteria differ from existing capabilities for remote monitoring of environmental compliance. In a revised manuscript, we would further emphasize the benefits of revised certification criteria that can be more easily monitored using existing satellite sensors. In addition to improving transparency, updating certification criteria to match monitoring capabilities would also bring RSPO more in line with industry commitments to zero-deforestation goals, including the New York Declaration on Forests.

Reviewer 2:

General Comments:
-I would like to see more information on how the area for the buffer analysis was selected. Why were the buffer areas around certified and non-certified plantations combined together? Or would it have made more sense to consider the plantation boundaries vs. plantations+buffers, while also keeping certified and non-certified separate?
I'm not sure if you might expect differences in fire activity between buffers around each type of plantation.

We appreciate the Reviewer's suggestion to provide additional information regarding the buffer areas and our analysis of deforestation and fire activity adjacent to oil palm plantations. Reviewer #1 also asked for clarification of the buffer analysis, and raised several similar questions regarding the potential for differences in buffers for certified and non-certified plantations.

The characteristics of buffer areas around certified and non-certified plantation boundaries were similar (see Figure R1, below), including the patterns of remaining forested area, forest loss, and fire-driven forest loss. In addition, oil palm plantations in Southeast Asia are frequently adjacent to other oil palm plantations (Figure 1), meaning that it is difficult to attribute buffer activities to only certified or non-certified neighbors. As a result, we analyzed fire activity and forest loss for a single set of buffer areas surrounding certified and non-certified plantations.

In the revised manuscript, we would clarify the characteristics of buffer landscapes in Section 2.1, including the fact that nearly 12% of the area within the 5km buffer was mapped as planted oil palm in 2010 (Gunarso et al., 2013; Carlson et al., 2013). Thus, the buffer region may reflect differences in management, in addition to differences in land use and land cover, based on the abundance of planted palm oil outside of large plantations.

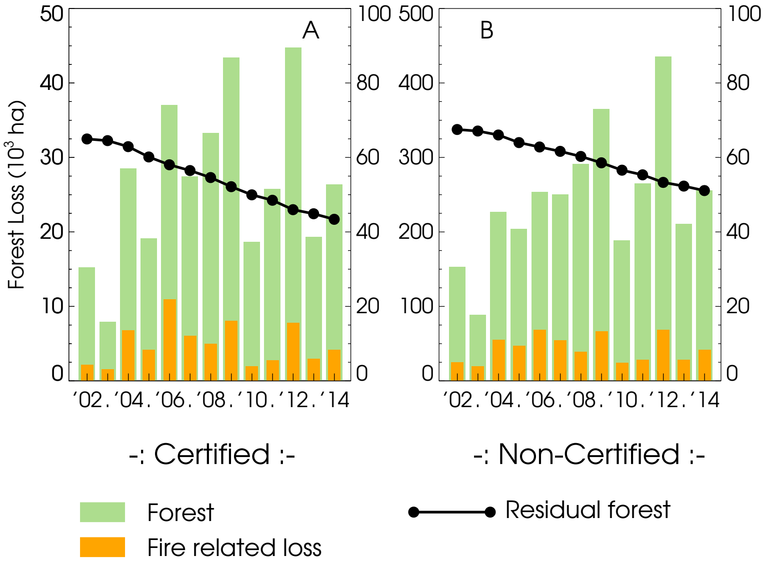

Figure R1: Forest (green) and fire-driven (orange) forest loss within a 5 km buffer surrounding certified and non-certified oil palm plantation boundaries. Solid black lines indicate residual forest cover as a percentage of the buffer area adjacent to certified and non-certified plantations.

Please also see specific comments below on this topic.
-Could there be differences in characteristics besides certification that are influencing the results? It's not clear to me as written if the authors considered other potential variables such as the level of access to plantations, size, whether part of the concession was previously developed, differences in specific provinces, etc. This might also help to address the statistical significance of the results.

We agree that certification is only one of the factors that may account for observed differences in forest loss and fire activity across certified and noncertified plantations. A large literature suggests that when it comes to certification, the producers with the lowest cost of entrance (e.g., the best environmental performance, large producers with sufficient capital) are typically those who become certified (e.g., Garrett et al., 2016). By not controlling for these factors, we cannot attribute observed lower fire rates to certification. However, our study does not attempt to discern the cause of observed results. Many consumers of palm oil are looking for a commodity with certain attributes (zero-fire, zero-deforestation). Our work informs these conversations because it suggests that RSPO certification is a good signal for such embodied characteristics. Additional studies that control for attributes such as plantation age, size, isolation, and governance are expected to provide further insights regarding the direct influence of certification on environmental outcomes. In our revised manuscript, we will clarify the goal of our study (to measure attributes of certified and not certified palm oil, rather than attributing causality to RSPO certification).

-Can the authors clarify in the text when they are discussing fires within a year of deforestation (fire-driven deforestation) vs. fires for plantation management/escaped fires?
Sometimes it's not clear to me which fire type is being discussed and the description in the methods section does not make this aspect clear.

Our study specifically identifies fires that are spatially and temporally coincident with forest loss, and we describe these fires as contributing to fire-driven deforestation. These fires are distinct from burning for plantation management (e.g., during oil palm replanting), accidental fires either man-made or due to lightening, or fires that occur in non-forest areas. In a revised manuscript, we would revise any wording that might be ambiguous in the description of the fire results.

Specific Comments:
-Pg. 2, Line 24: What about the % certified within Southeast Asia?

In a revised manuscript, we would clarify that most certified plantations are within Southeast Asia:
"By 2016, the RSPO had certified 2.83 Mha of oil palm that produced 10.8 million tons of palm oil, or approximately 17% of global palm oil production, with >90% of certified areas in Southeast Asia (RSPO, 2016)."

-Pg. 3, Line 31: Do you have the date of certification for each plantation or is it only known to have occurred between 2009-2015?

In our original manuscript, the analysis considered the time series of annual fire activity and deforestation for certified and non-certified plantations, based on the extent of certified plantations as of April, 2015. This ever/never treatment of certification did not specifically consider the date of certification for each plantation. The RSPO Principles & Criteria prohibit deforestation of primary or HCV forest after Nov. 2005 and all fire activity, in accordance with laws in Indonesia, PNG, and Malaysia. As a result, our analysis captures the full range of company commitments to sustainable palm oil production covered by the Principles & Criteria, rather than only the actions following the receipt of the RSPO certificate.

However, the date of certification is known for each plantation in our database. In a revised manuscript, we propose to include estimates of the total forest loss, fire-driven forest loss, and total fire activity that occurs on the subset of certified plantations that have already received their RSPO certificate (See tables B2, B3, and B4, below). This detailed breakdown provides a more robust basis for evaluating forest loss and fire activity in certified plantations.

Table B2: Total and fire-driven forest loss for oil palm expansion in Indonesia from 2002-2014 within the certified and non-certified plantations.

Year	**Certified**				**Non-Certified**		**Buffer 5km**	
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Fire-driven loss (ha))	Total loss (ha)	Fire-driven loss (ha)
2002	12,646		4,961		86,179	21,890	184,140	29,713
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2010	6,267	(8)	306	(0)	120,598	14,330	228,111	28,634
2011	7,105	(23)	308	(42)	240,864	22,776	316,644	34,771
2012	9,163	(25)	495	(25)	334,453	45,787	512,886	80,585
2013	6,628	(50)	480	(82)	176,080	21,815	245,738	32,635
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Table B3: Total and fire-driven forest loss for oil palm expansion in certified plantations in Malaysia and Papua New Guinea during 2002-2014. All areas are given in hectares (ha).

Year	**Malaysia**				**Papua New Guinea**			
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)
2002	14,870		912		3,959		1,244	
2003	6,563		791		1,645		301	
2004	13,522		1,912		3,279		721	
2005	6,410		506		1,242		252	
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2008	7,381	(2)	91	(0)	1,188	(34)	116	(7)
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2013	3,261	(50)	85	(78)	756	(100)	0	(100)
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Table B4: Total MODIS fire detections for certified plantations, including post-certification fire detections.

	Indonesia		**Malaysia**		**Papua New Guinea**	
Year	Total fire detections	Post-Certification fire detections (%)	Total fire detections	Post-Certification fire detections (%)	Total fire detections	Post-Certification fire detections (%)
2001	169		124		37	
2002	1782		87		130	
2003	716		71		64	
2004	1821		87		130	
2005	1008		128		39	
2006	2712		17		83	
2007	197		12		61	
2008	87		9	(0)	43	(7)
2009	483	(0)	22	(0)	31	(0)
2010	72	(8)	18	(28)	44	(95)
2011	196	(29)	12	(50)	18	(67)
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2013	128	(55)	11	(55)	54	(100)
2014	361	(73)	35	(69)	52	(100)
2015	656	(100)	26	(100)	136	(100)

-Pg. 4, Line 4: Was each individual plantation owned by a separate company, or was there overlap in ownership?

RSPO member companies typically have more than one oil palm plantation, although member companies may have both certified and non-certified plantations, as not all plantations must be certified upon joining the RSPO. In our revised manuscript, we will clarify this nested structure.

-Pg. 4, Line 10: Can you give more details on how planted oil palm was detected and if there were any differences between the three studies?

The three data sources for planted oil palm (i.e., Gunarso et al., 2013; Carlson et al., 2013; TW, 2015) identified oil palm using visual interpretation based Landsat and other high-resolution datasets (i.e., Quickbird). Differences in the date of Landsat or other imagery, including cloud cover, may contribute to potential differences in the estimated extent of oil palm. When multiple estimates were available for the same epoch, we used the combined area from all sources as a more conservative estimate of the extent of planted oil palm.

-Pg. 4, Line 29: How was the 5km buffer selected? Were any differences considered between small vs. large plantations?

We selected a single buffer size (5 km) to evaluate the patterns of fire-driven deforestation, forest loss, and total fire activity adjacent to palm oil plantations. This buffer was calculated for all plantations combined, given that certified and non-certified plantations are frequently adjacent to one another. In general, palm oil plantations in this study were large; in Indonesia, the average size certified plantations (10,700 ha) was comparable to that of non-certified plantations (7,300 ha).

-Pg. 5, Line 12: Could there be any effects of having a 5 year time step for the oil palm datasets vs. the annual deforestation datasets?

The extent of planted palm oil was used to exclude forest loss likely associated with replanting of existing palm oil plantations, rather than clearing of remaining forest area to establish new plantations. Given this approach, estimates of annual forest loss outside of mapped oil palm were considered new forest loss (ie, we assumed that it would be unlikely for planted areas to be established and re-cleared within a single 5-year time step).

-Pg. 5, Line 23: Can you clarify if the certification timing was similar for all of these plantations (2009?) or if it varied across the study area? Could some of the plantations in the certified category have only been certified towards the end of the study period?
If the dates are not known, I would appreciate a discussion at some point in the paper on how this could impact results.

Please see answer above. As noted, the dates of certification vary between 2008 and 2015 for individual plantations. The revised tables (B2, B3, B4) now provide a breakdown of forest loss and fire activity associated with plantations that have already received their RSPO certification, because certification itself (rather than intent to certify) may also impact fire and deforestation dynamics since it includes on the ground visits by auditors.

-Pg. 5, Lines 23-24: Can you comment here or in the discussion on why this could be higher? Were these plantations easier to access or were there other factors that lead to higher deforestation pre-certification? Are these results statistically significant?

Higher rates of forest loss prior to a specific cutoff date (i.e., 2006 or 2009) may indicate an effort to strategically clear forests before restrictions associated with certification begin. The question of statistical significance for differences in clearing rates would necessitate a detailed look at individual plantation characteristics, rather than all certified plantations as a group, in order to control for selection bias of certification. In a separate study (Carlson et al., under review), we evaluate rates of forest loss and total fire activity for matched certified and non-certified concessions.

-Pg 6, Line 1: What do you mean by management classes? Certified, non-certified, and buffers?

Yes, this reference was to certified plantations, non-certified plantations, and buffer areas. In a revised manuscript, we would change this terminology to clarify that this result applied to all three categories of land management.

-Pg. 6, Line 1: Can you mark el nino years on the figure for reference? Any differences depending on the strength of the el nino?

In a revised manuscript, we would mark the El Niño years in Figure 2, as suggested. As the reviewer points out, the strength and duration of El Niño events are somewhat variable (see Figure R2, below). Such differences do influence the total fire activity in different El Niño years (e.g., van der Werf et al., 2008, Field et al., 2016). However, the goal of this work was to compare fire activity across land management classes (certified plantations, non-certified plantations, and buffer areas) in each year, rather than the absolute amount of fire, since oil palm plantations account for a small proportion of total burning in Southeast Asia during El Niño events (e.g., certified plantations in Indonesia account for only 0.5% of all MODIS fire detections in 2015).

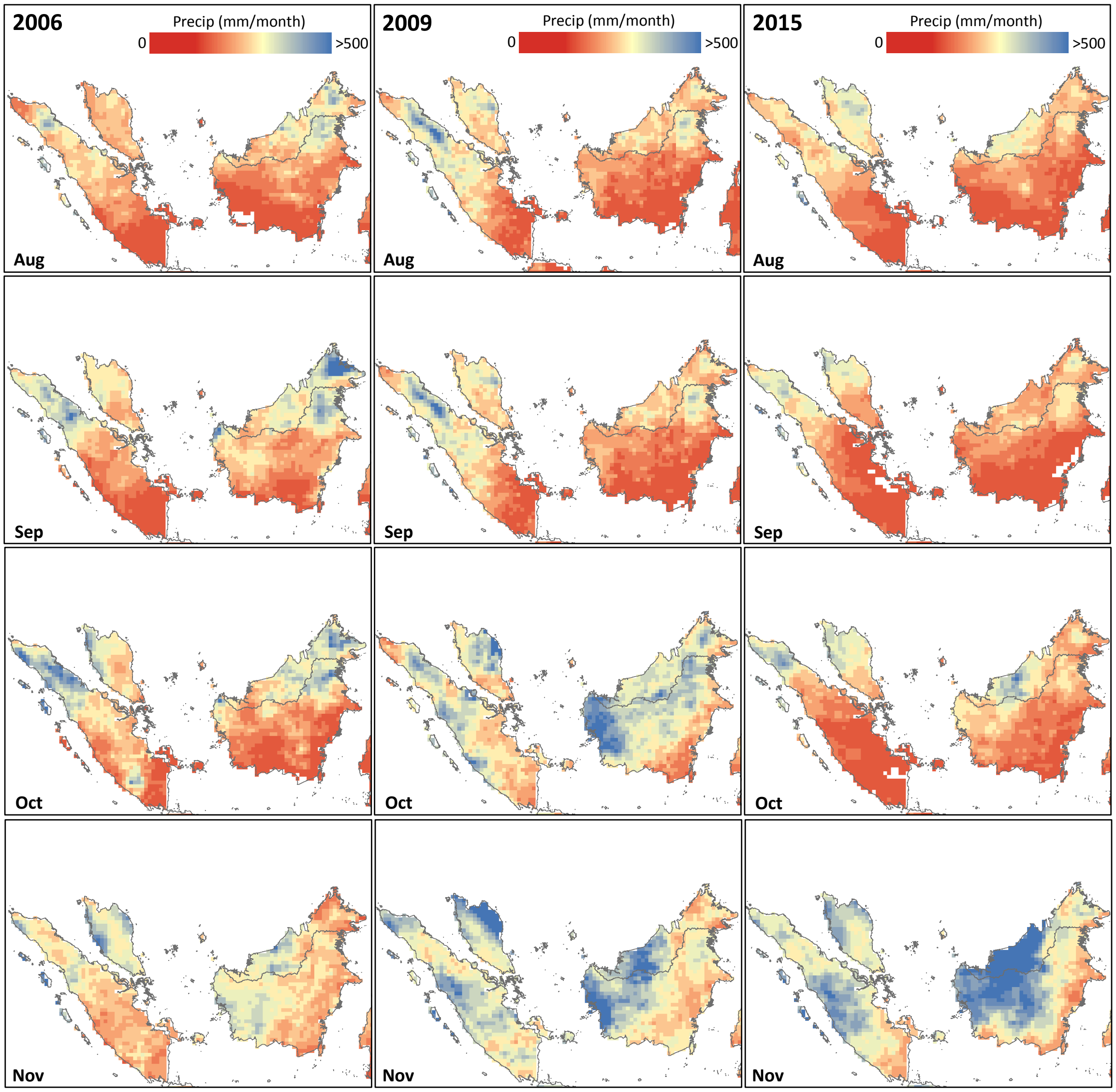

Figure R2: Monthly precipitation for Indonesia and Malaysia from the Tropical Rainfall Measuring Mission (TRMM, 3B43v7) during peak fire months for El Niño years (2006, 2009, and 2015). The spatial distribution of precipitation was similar in 2006 and 2015, whereas the region received more precipitation in October during the 2009 El Niño event.

-Pg. 6, Line 6: Were the number of dry years consistent between the two periods of comparison?

This particular reference (Pg 6, Line 6) refers to deforestation rates, not fire activity. As a result, we would not expect the number of dry years to influence observed rates of forest loss.

-Pg. 6, Line 15: Again, I'm wondering if you know about differences in certification timing among the three areas?

Yes, as described above, the date of certification is known for all certified plantations in this study. The timing of certification differs among plantations. However, all companies that are members of RSPO agree to the Principles & Criteria of certification and commit to eventually certify all of their mills. The P&C specify reductions in deforestation and fire use that predate the receipt of the RSPO certificate. For example, certification dates for plantations in this study span the period between 2008 to 2015, yet companies with certified plantations joined RSPO as early as 2004. In a revised manuscript, we would clarify the sequence of events that predate certification, including the timing of membership as opposed to certification for member-held plantations.

-Pg. 6: Line 28: Can you give a comparison of the strength of these different El Nino events?

As shown in Figure R2, above, the strength of recent El Niño events is somewhat variable, as documented in a recent studies (e.g., Field et al., 2016). A full exploration of the evolution and duration of El Niño events is beyond the scope of this study (see Figure 5 in Field et al. (2016) for an analysis of precipitation, fire density, and other characteristics of previous El Niño events. The analysis in this study compares fire activity across plantation and buffer classes in each year, but does not compare absolute fire activity across El Niño events where it would be necessary to control for the strength of El Niño events and time-varying aspects of plantation management, including certification.

-Pg. 6, Line 35: I'm not sure I understand exactly what you did here. For the annual fire detections, did you address the difference in temporal sampling between the different datasets? What detection differences might you expect between the different sensors and how could this influence comparisons?

Figure 6 provides an indication of the degree of consistency between MODIS and new high-resolution active fire detections from VIIRS and OLI for 2014 and 2015. The accompanying map panels highlight the additional detail available from higher-resolution observations—key advances to support routine monitoring of environmental compliance under RSPO or other certification approaches. The goal was not a validation of current algorithms—these questions have been addressed in previous research (e.g., Schroeder et al., 2014). Instead, Figure 6 documents how data from new sensors are consistent with the long-term observations from MODIS and also offer new potential for transparency in monitoring environmental compliance under RSPO or other certification efforts.

-Pg. 7, Line 10: I thought that the Cattau study was focused on concessions that were previously cleared or planted, so wouldn't you expect differences between that study vs. fires used for deforestation as examined here? Or are you considering management fires (see general comment #3)? Not sure if I'm missing something here, so a clarification would be appreciated.

Cattau et al. visually inspected a small number of oil palm concessions (n=53) using data in Google Earth and did not identify evidence of additional palm oil expansion during the period of their study (2012-2015). In contrast, we used satellite-based estimates of forest loss and planted oil palm to separate forest loss and fire activity associated with remaining forest areas from fire detections on existing cleared or planted palm. By reporting both fire-driven forest loss and total fire activity, we are able to separate the fire detections associated with expanding production from other fire types, including intentional management or accidental burning. We are therefore able to address somewhat different questions from Cattau et al., based on the larger sample size of plantations across three countries, longer study period (2002-2015), and separation of fire-driven deforestation from other fire types. Interannual variability in fires associated with forest loss and residual fires related to management or accidental burning (see figure 5) specifically investigates the degree to which fire-driven deforestation occurs on certified plantations, non-certified plantations, and surrounding landscapes in comparison with other fire types. Cattau et al. do not address the question of how fire is used during forest conversion, either as a component of the emissions embodied in certified palm oil or as a source of fires on the landscape during drought years.

-Discussion: If you feel it's warranted, could you comment on whether your work relates to the findings by Gaveau et al. (2016) on the timing of deforestation for oil palm plantations? Gaveau, D. L. A. et al. Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. Sci. Rep. 1–13 (2016). doi:10.1038/srep32017

Gaveau et al. argue that much of the oil palm expansion in Indonesian Borneo was on previously cleared lands, rather than intact forests. Our study differs from this previous work in several respects. First, we quantified forest loss, fire-driven forest loss, and total fire activity within oil palm plantations. We used existing maps of planted oil palm to isolate changes to remaining forest cover within plantations, and we therefore assume that all forest conversion is for palm oil expansion. In contrast, Gaveau et al. visually interpreted satellite data to identify planted oil palm for different epochs, similar to data products in our study (e.g., Gunarso et al., 2013; Carlson et al., 2013; TW, 2015). We do not attempt to identify the year of planting relative to the year of forest loss. Second, our study only examines certified plantations in Malaysia, not non-certified plantations. In our study, a higher proportion of new planted palm came from forest in Indonesia (59%) than Malaysia (20%) between 2001-2010. Some differences may be expected in our results based on the extent of plantation areas. In a revised manuscript, we would comment on the difference between our results and the findings from Gaveau et al., while clarifying that different results may reflect the difference in geographic domains and plantation datasets between studies.

Technical Comments:

-Pg. 3, Line 25: Should it be section 2.1? (Also the rest of the subheadings in this section)

We have changed the section numbers accordingly.

-Pg. 5, Line 1: The VIIRS definition just repeats the first part of the sentence?

We have removed the repeated definition sentence.

-Pg, 5: Line 14: Can you add a supplementary figure show the distribution of peatlands? We only have the subsets from Figure 1.

In a revised manuscript, we would include the full peatland map as a supplemental figure (see figure R3 below).

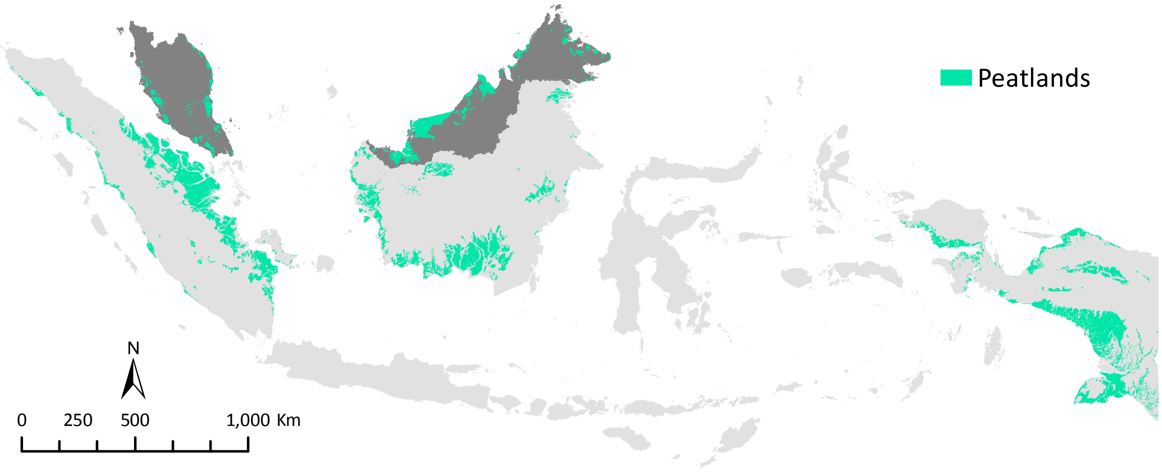

Figure R3: Extent of peatlands in Indonesia and Malaysia (Wahyunto et al., 2003; 2004;2006 and WI, 2016).

-Pg. 5, Line 22: Missing %.

We have included %.

-Pg. 6, Line 29: What were the peak burning months?

August, September, and October. We have added the months in the main text, based on the analysis presented in Figure A3.

-Figure 1: Is it possible to color code the zoomed in subsets by certified vs. non certified? Perhaps with some shading of the peatlands instead? This might make the figure too busy but it would be nice to see the spatial details.

We are unable to provide the information on the location of certified plantations.

Reviewer 3:

The authors compare fire activity and deforestation between RSPO-certified and noncertified oil palm plantations in Southeast Asia, arguing that RSPO certification has led to reduced fire activity during dry years. This is a well-written paper and the overall result is important. My only significant concern is the assumption that dry conditions during the big fire years were the same with respect to the locations of certified and non-certified plantations.

We appreciate the Reviewer's recognition of the importance of this study. As the Reviewer suggests, the spatial distribution and duration of precipitation anomalies during El Niño events is somewhat variable. In our study, certified and non-certified plantations can only be compared for Indonesia. As indicated in Figure 1, certified and non-certified plantations in Indonesia are clustered in similar locations: 73% of certified plantations were directly adjacent to one or more non-certified plantations, and 89% of certified plantations were within 10 km of a non-certified plantation. Given this clustering, and the spatial resolution of precipitation estimates from the TRMM satellite (0.25 degree resolution), we assume that El Niño events are likely to influence certified and non-certified plantations in a similar fashion. Precipitation distributions vary for recent El Niño events (see Figure R2, below). However, the main emphasis of this study was to compare among certified, non-certified, and buffer areas during the same year. In a revised manuscript, we would further emphasize the relative comparison among certified plantations, non-certified plantations, and buffer areas in a given year.

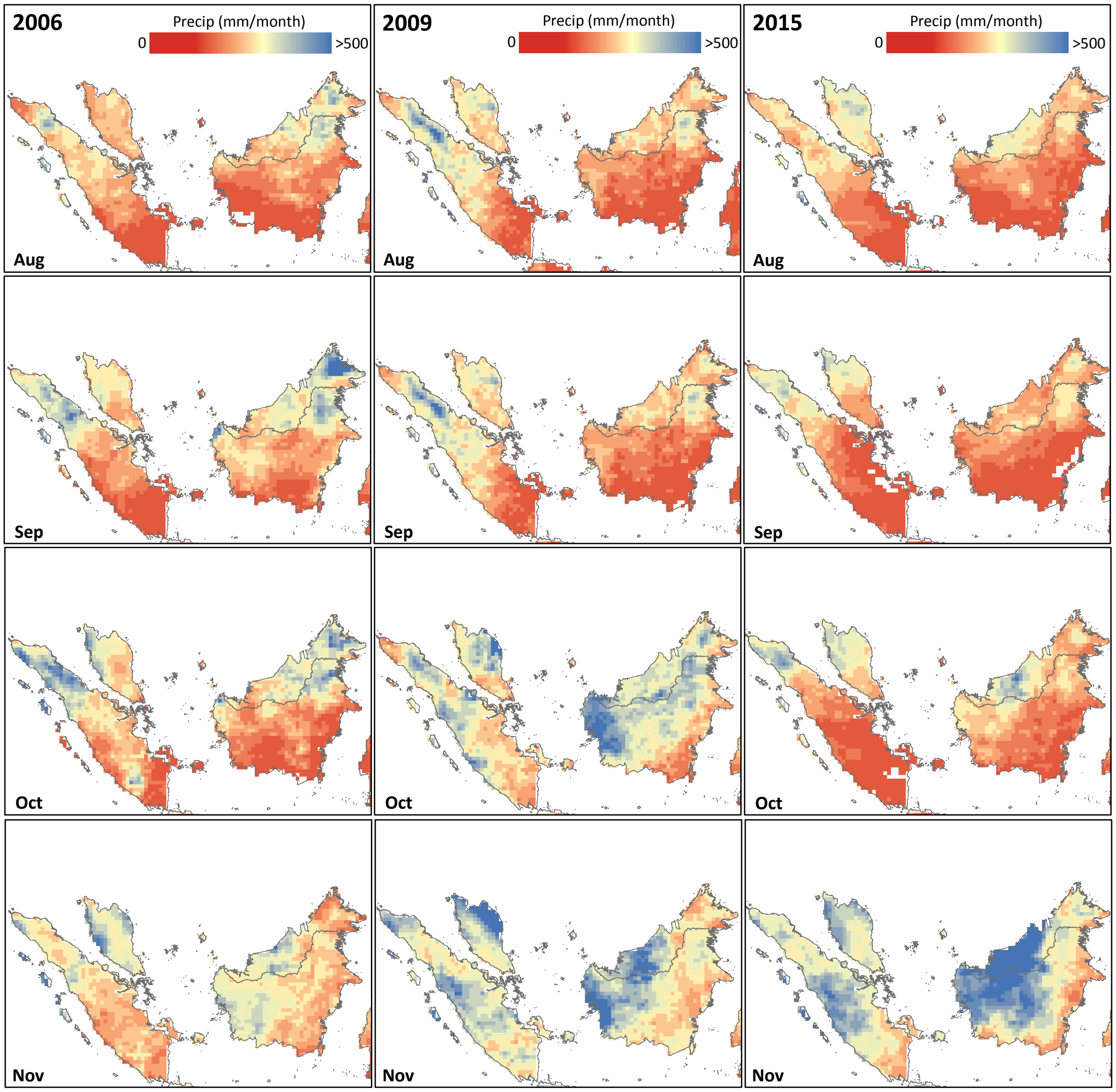

Figure R2: Maps show monthly totals of the precipitation patterns for Indonesia and Malaysia from Tropical Rainfall Measuring Mission (TRMM, 3B43v7) at 0.25° resolution during the dry season in El Niño years of 2006, 2009, and 2015. The spatial distribution of dryness was severe in El Niño year 2015, but dry conditions extended until November in 2006.

Comments P1L21: should this be 'did not stop altogether'?

Yes, we have changed to "did not stop altogether"

P3L30: I didn't understand the '(ever)' and '(never)' wrt certified and non-certified

In our study, "ever" refers to oil palm plantations that ever got certified after the cutoff year (i.e., year 2009). Whereas, the "never" refers to non-certified plantations—those plantations that were not certified between 2009 and 2015. However, many of the non-certified plantations are in the process of certification and may get certified in future years.

P4L20: The end of this sentence implies that Southeast Asia has little rainfall season- ality, which I don’t think you mean to say.

This sentence refers to the persistent cloud cover in tropical regions without regular dry seasons, typically considered months with <100 mm rainfall. In a revised manuscript, we would clarify this statement as “regions with persistent cloud cover” to avoid confusion between rainfall seasonality and drier conditions when lower cloud cover facilitates satellite remote sensing.

P6L28: How are you excluding the possibility that the certified plantations just weren’t as dry in 2015 compared to, say, 2006? Figures A3 and Figure 5 clearly show a drop in fire activity over the analysis period over the certified plantations, but from Figure 1, these plantations are not evenly distributed across Sumatra and Kalimantan. It’s possible that these regions, for example south-central Kalimantan, were just wetter in 2015 than previous years, given that regional rainfall can vary across El Niño years. Or perhaps they were drier, in which case your argument about RSPO effects is strengthened. Either way, regional rainfall needs to be looked at or mentioned as a possible factor.

We agree with the reviewer that the spatial distribution of plantations is a potential source of variability that was not directly addressed in our original manuscript. In addition to the analysis of proximity, as described above, it is possible to characterize the time series of fire activity for the closest certified and non-certified plantations. In Figure R3, below, we show the time series of MODIS fire detections (similar to Figure 5), restricting the analysis to non-certified plantations within 50 km of one or more certified plantations in Indonesia (N=1076 of 1536 non-certified plantations). By limiting the comparison to nearby plantations, we can more confidently assume that these regions experienced similar precipitation patterns (as shown in Figure R2 using 0.25 degree TRMM data). Figure R3 shows a similar pattern of interannual variability as Figure 5, and the relative comparison among certified and non-certified plantations is consistent with Figure 5 for El Niño years, including 2006, 2009, and 2015. We therefore conclude that the relative difference between certified and non-certified plantations in these years is not driven by differences in the spatial distribution of oil palm plantations.

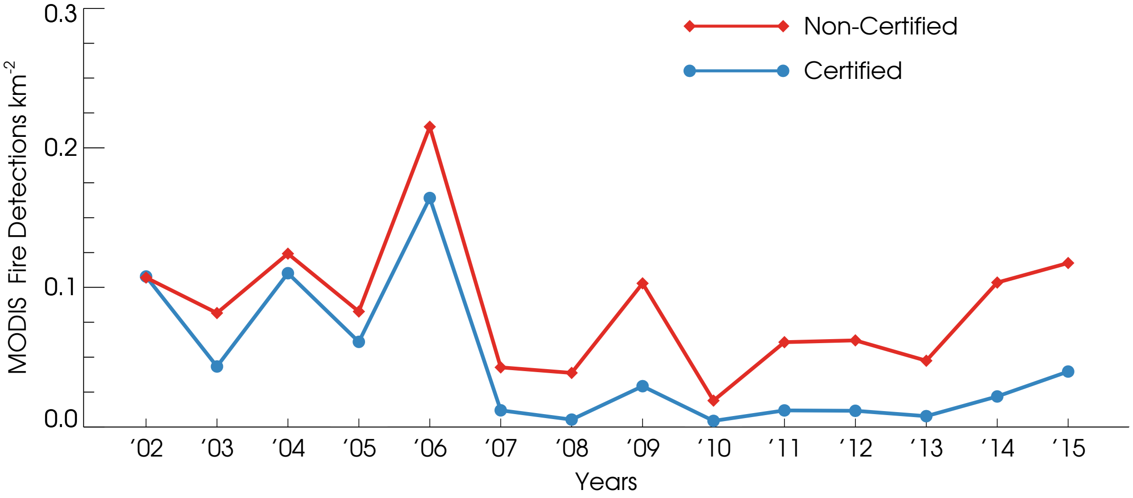

Figure R3. Time series of MODIS active fire detections, as in Figure 5, for certified plantations and the subset of non-certified plantations within 50 km of a certified plantation in Indonesia.

P7L9: change ‘direct’ to ‘directly’

We have changed to ‘directly’

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Managing fire risk during drought: the influence of certification and El Niño on fire-driven forest conversion for oil palm in Southeast Asia

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Abstract. Indonesia and Malaysia have emerged as leading producers of palm oil in the past several decades, expanding production through the conversion of tropical forests to industrial plantations. Efforts to produce "sustainable" palm oil, including certification by the Roundtable on Sustainable Palm Oil (RSPO), include guidelines designed to reduce the environmental impact of palm oil production. Fire-driven deforestation is prohibited by law in both countries and a stipulation of RSPO certification, yet the degree of environmental compliance is unclear, especially during El Niño events when drought conditions increase fire risk. Here, we used time series of satellite data to estimate the spatial and temporal patterns of fire-driven deforestation in and around oil palm plantations. In Indonesia, fire-driven deforestation accounted for one quarter of total forest losses in both certified and non-certified plantations. After the first plantations in Indonesia received RSPO certification in 2009, forest loss and fire-driven deforestation declined in certified plantations but did not stop altogether. Oil palm expansion in Malaysia rarely involved fire; only 5% of forest loss in certified plantations had coincident active fire detections. Interannual variability in fire detections was strongly influenced by El Niño and the timing of certification. Fire activity during the 2002, 2004, and 2006 El Niño event was similar among oil palm plantations in Indonesia that would later become certified, non-certified plantations, and surrounding areas. However, total fire activity was 75% and 66% lower in certified plantations than non-certified plantations during the 2009 and 2015 El Niño events, respectively. The decline in fire activity on certified plantations, including during drought periods, highlights the potential for RSPO certification to safeguard carbon stocks in peatlands and remaining forests in accordance with legislation banning fires. However, aligning certification standards with satellite monitoring capabilities will be critical to realize sustainable palm oil production and meet industry commitments to zero deforestation.

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1 Introduction

Global production of agricultural commodities such as palm oil has risen steadily in recent decades in response to market demand (USDA, 2009 , 2010 , 2016). Southeast Asia's palm oil sector has grown through expansion of oil palm plantations in Malaysia, Indonesia, and more recently, Papua New Guinea (Gunarso et al., 2013; Carlson et al., 2013; Miettinen et al., 2016a; Vijay et al., 2016). By 2014, Indonesia and Malaysia accounted for nearly 69% of harvested oil palm area worldwide (FAO, 2016).

In the past decade, Indonesia had the highest rate of forest loss of any country in Southeast Asia (Hansen et al., 2013; Margono et al., 2014; Kim et al., 2015), spurred by rapid forest conversion for oil palm and other industrial plantations (Carlson et al., 2012; Gunarso et al., 2013; Abood et al., 2015). Between 1990-2010, more than one third of new oil palm plantations replaced forested landscapes in Southeast Asia (Gunarso et al., 2013; Gaveau et al., 2016), with rates as high as 90% in regional hotspots such as coastal West Kalimantan, Indonesia (Carlson et al., 2013). Conversion of primary and logged forests for oil palm, including vast areas with deep organic peat soils, contributed to significant greenhouse gas (GHG) emissions from fire, decomposition, and peat oxidation (Page et al., 2002; van der Werf et al., 2008; Hooijer et al., 2012; Ramdani and Hino, 2013; Field et al., 2016; Huijnen et al., 2016). Environmental concerns with palm oil production extend beyond GHG emissions, however, as forest loss threatens biodiversity (Pimm et al., 2014; Vijay et al., 2016) and particulate emissions from fires are a major public health concern in Indonesia and downwind population centers such as Singapore (Murdiyarso et al., 2004; Gaveau et al., 2014; Kunii et al., 2002; Reddington et al., 2014; Marlier et al., 2015; Chisholm et al., 2016; Johnston et al., 2015).

Palm oil is the fastest growing certified agriculture commodity, and Indonesia accounted for >50% of certified production areas in 2016 (Potts et al., 2014; RSPO, 2016). The push for certification within the palm oil industry reflects a growing consumer awareness of GHG emissions from palm oil expansion and peat oxidation and an overall rise in producer and consumer interest in "sustainable" and deforestation-free products (UNCS, 2014; Butler, 2015; McCarthy et al., 2016). The Roundtable on Sustainable Palm Oil (RSPO) certification is the most widely adopted certification standard. By 2016, the RSPO had certified 2.83 Mha of oil palm that produced 10.8 million tons of palm oil, or approximately 17% of global palm oil production, with >90% of certified areas in Southeast Asia (RSPO, 2016). Specific principles and criteria of RSPO certification promote sustainable palm oil production and processing (Garrett et al., 2016; RSPO, 2004, 2015b). Among other provisions, RSPO certification prohibits conversion of primary and high conservation value (HCV) forests and bans fire use for land clearing in compliance with the Indonesian moratorium on fire (RSPO, 2007; RSPO, 2013 ; Edwards and Heiduk, 2015). Companies interested in certification first become members of the RSPO and are subjected to the Principles & Criteria (P&C), including the prohibition on new plantings through deforestation of primary or HCV forests after Nov. 2005 without compensation (Criterion 7.3, RSPO 2013). However, the RSPO does not independently monitor deforestation within member plantations. RSPO members companies are notified of satellite fire detections on their plantations, and a description of fire incidents is included in monthly reports to RSPO. Recent fire activity has been assessed for a subset of

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palm oil concessions in Indonesia (Cattau et al., 2016), but the use of fire for forest conversion on oil palm plantations has not previously been quantified.

Improving estimates of fire-driven deforestation is critical to assess environmental compliance by oil palm plantations, reduce uncertainties in deforestation carbon emissions (Le Quéré et al., 2015; Houghton et al., 2012; van der Werf et al., 2009b), and characterize ignition sources that may give rise to uncontrolled burning during drought periods (Carlson et al., 2012; Cattau et al., 2016). The timing of GHG emissions from forest conversion to oil palm depends on the degree of fire use for deforestation (DeFries et al., 2008; Houghton et al., 2012), including the proportion of clearing activity through fire and the combustion completeness of initial or repeated burning (van der Werf et al., 2009a). Fires are common in industrial plantations and smallholder properties (Stolle et al., 2003; Austin et al., 2015; Marlier et al., 2015; Miettinen et al., 2016b; Cattau et al., 2016), yet the link between fire activity and forest conversion is unclear. Many estimates of carbon emissions from tropical forest conversion report committed fluxes without separating fire and decomposition losses (Koh et al., 2011; Carlson et al., 2012; Austin et al., 2015). Previous studies with bookkeeping or biogeochemical models suggest that fire accounts for 30% (Houghton and Hackler, 1999) to 50% (van der Werf et al., 2009a) of carbon emissions from aboveground biomass during forest conversion in Southeast Asia—a broad range that applies to all forest conversion, not strictly to oil palm expansion. Fires are not restricted to forested areas; El Niño conditions suppress precipitation over large parts of Southeast Asia, leading to widespread fire activity during drought periods, particularly in carbon-rich peatlands (Page et al., 2002; van der Werf et al., 2008; Field et al., 2009, 2016). Understanding the contribution from fire-driven deforestation to total fire activity is therefore a critical part of mitigating fire risk during drought years (e.g., Chen et al., 2016).

Here, we combined time series of satellite data on forest loss and active fire detections with locations of oil palm plantations to assess fire-driven forest and peatland conversion in and around oil palm plantations. The combination of land management, forest loss, and active fire data provided an opportunity to evaluate the relative contributions from different fire types to spatial and temporal variability in satellite fire detections. Our study addressed three primary questions regarding oil palm expansion: 1) What fraction of forest and peat forest conversion for oil palm involves fire? 2) Does certification alter fire use for forest conversion or the frequency of management or accidental fires in plantation areas? and 3) During El Niño years, do certified plantations have fewer satellite fire detections compared to non-certified plantations and surrounding lands? Characterizing fire-driven deforestation is critical to evaluate the influence of RSPO certification on fire activity and to improve estimates of GHG emissions from oil palm expansion.

2 Material and Methods

2.1 Oil Palm Plantations

The government of Indonesia allocates land for oil palm production to companies for a limited period of time. We separated leases for oil palm production into two categories, certified and non-certified plantations. Certified plantations are properties

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certified by the RSPO; non-certified plantations are properties allocated by the Indonesian government to companies but that are not certified, even if they are held by RSPO members. Comparisons between certified (ever) and non-certified (never) plantations considered forest loss and fire activity over three time scales: 1) following the benchmark date for compliance with RSPO Criterion 7.3 (Nov. 2005), 2) following the first issuance of RSPO certificates to Indonesian producers in 2009, and 3) following the date of certification for individual plantations. Boundaries of certified plantations were compiled from several sources, including boundary polygons provided by the RSPO, digitized boundaries from RSPO audit reports, and spatial data on plantation boundaries from RSPO member companies provided in annual communication of progress (ACOP) reports (RSPO, 2015a). Boundaries of non-certified plantations were obtained from a database of oil palm plantations published by Greenpeace (Greenpeace, 2016) and supplemented with non-certified plantations held by RSPO members, as indicated in ACOP reports (RSPO, 2015a) or by Sawit Watch (2013). In total, we analysed 154 certified and 1536 non-certified plantations boundaries for Indonesia (Fig. 1). Data on the location and certification date of certified plantations were also available for Malaysia (n = 119) and Papua New Guinea (n = 10), but boundaries of non-certified plantations were not available.

We used maps of planted oil palm to identify established plantations within certified and non-certified plantations in Indonesia, Malaysia, and Papua New Guinea. Data on the extent of planted oil palm were compiled from three sources: Gunarso et al. (2013) for 2000, 2005, and 2010; Carlson et al. (2013) for 2000, 2005, and 2010; and Transparent World (TW, 2015) for 2014. When multiple estimates were available for the same epoch, we used the combined area from all sources as a more conservative estimate of the extent of planted oil palm. Only non-certified plantations with evidence of planted oil palm by 2014 were included in this study.

We evaluated forest loss and fire activity for a single set of 5 km buffers surrounding both certified and non-certified plantations in Indonesia. Recent fire emergencies have intensified the debate over the source of fire ignitions during El Niño and other drought events (e.g., Austin et al., 2015). The 5km buffer was chosen to capture the potential influence of forest loss and fire activity on the surrounding landscape, including the direct fire spread from adjacent lands into palm oil plantations, wind-blown embers from nearby fires, and the most acute impacts of smoke on both human health and ecosystems. Oil palm plantations in Southeast Asia are frequently adjacent to other oil palm plantations (Fig. 1), making it difficult to attribute buffer activities to only certified or non-certified neighbours. We therefore analysed a single set of buffer areas to evaluate forest loss and fire activity surrounding large oil palm plantations. Nearly 12% of the area within the 5km buffer was mapped as planted oil palm in 2010 (Gunarso et al., 2013; Carlson et al., 2013). As for plantations, areas of planted oil palm were excluded from estimates of forest loss in buffer areas. However, total fire activity in the buffer region may reflect differences in oil palm management, in addition to differences in land use and land cover, based on the abundance of planted palm outside of the large certified and non-certified plantations.

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2.2 Forest definition, cover, and loss

Estimates of forested area and forest loss fundamentally depend on the definition of forest cover (Sexton et al., 2016). Countries may use canopy cover thresholds between 10-30% for reporting under the United Nations Framework Convention on Climate Change (UNFCCC) REDD+ framework (UNFCCC, 2002). The Indonesian government uses the United Nations Food and Agriculture Organization (FAO) Forest Resource Assessment (FRA) definition of forest as canopy cover ≥ 30% (FAO, 2010; MoF, 2008), at the high end of the REDD+ range. Therefore, we used the >30% canopy cover threshold in this study to be consistent with the Indonesian forest definition. The higher canopy cover threshold also reduced ambiguity associated with discriminating tropical forests from other land cover types in remote sensing data for regions with persistent cloud cover, such as Southeast Asia. Forest and non-forest areas were separated using Landsat-based estimates of fractional tree cover in 2000 (Hansen et al., 2013). Estimates of annual forest loss between 2002-2014 (Hansen et al., 2013) were used to identify the timing of forest conversion in and around plantations.

2.3 Active fires

We used the time series of active fire detections from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites to evaluate the spatial and temporal patterns of daily fire activity during 2002-2015. The global monthly fire location product (MCD14ML) identifies the location of actively burning fires and thermal anomalies at the time of satellite overpass at 1 km nominal spatial resolution (Giglio et al., 2003). Fire pixel counts from Terra and Aqua MODIS sensors were combined using a 1km grid to evaluate monthly and annual fire activity from 2002 to 2015. We compared fire pixel density (km^{-2}) across certified plantations, non-certified plantations, and a 5km buffer region surrounding both certified and non-certified plantations.

For 2014 and 2015, higher spatial resolution active fire detections were used to confirm patterns in 1 km MODIS fire data. These complementary active fire detections were derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) I-band (375m) on the Suomi-National Polar orbiting Partnership (S-NPP) (Schroeder et al., 2014) and Landsat-8 Operational Land Imager (OLI) data at 30 m resolution (Schroeder et al., 2015). The finer spatial resolution of these fire data capture additional details regarding fire activity that can be difficult to evaluate at MODIS resolution, including the precise location of active fire fronts, separation of flaming and smouldering fires (Elvidge et al., 2015), and detection of small and/or lower intensity fires (Schroeder et al., 2015)—an important component of fire activity in agricultural landscapes (Randerson et al., 2012). In this study, the improved spatial resolution of VIIRS and OLI fire data aided the attribution of active fires to specific land management areas.

1.4 Fire-driven forest conversion for oil palm expansion

We combined satellite remote sensing data on forest cover (2000; Hansen et al., 2013), forest cover change (2002-2014; Hansen et al., 2013), and active fire detections (2001-2014; Giglio et al., 2003) to identify fire-driven forest conversion in

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certified and non-certified plantations. Our assessment excluded forested areas identified as oil palm (Gunarso et al. (2013); Carlson et al. (2013)). Deforestation within oil palm plantations was therefore limited to Hansen et al. (2013) tree cover loss in forested areas (tree cover >30%) outside of planted palm. Oil palm expansion into peat forests was assessed using peatland layers created by Wahyunto et al. (2003, 2004, 2006) and Wetlands International (WI, 2016). Co-located forest loss and active fire detections were considered fire-driven deforestation. Given the potential for fire activity to pre-date the detection of forest loss (Morton et al., 2008), active fire data from the year of forest loss and one year before were combined to identify fire activity associated with forest conversion.

3 Results

3.1 Certification and Fire-driven Deforestation

In Indonesia, forest loss in and around oil palm plantations reduced remaining forest cover by 30-36% between 2002-2014 (Fig. 2). Gross forest loss within plantations but outside of planted palm areas totalled 3.59 Mha (Table 1). Average annual rates of forest loss were similar in certified (1.25% yr^{-1}) and non-certified plantations (1.72% yr^{-1}) over this period. However, trends in annual forest loss differed between certified plantations and both non-certified and buffer areas. Following the cut-off date for new deforestation (Nov. 2005), rates of forest clearing actually increased in plantations that would later be certified (2006-2008, 38,636 ha yr^{-1}) before declining sharply after the first certificates were issued (2009-2015, 10,943 ha yr-1, Table B2). Between 2009 and 2012, the majority of forest loss occurred on plantations that had not yet received RSPO certification (Table B2), whereas plantations with certificates accounted for most forest losses identified in 2013-2014. Patterns of peat forest loss on certified plantations were similar to lowland forest loss outside of peat (Fig. 2, Table B3), with a peak in peat forest loss around the 2006 El Niño event followed by a steady decline after 2009. In contrast, rates of forest and peat forest loss in non-certified plantations increased over time, with peak clearing in 2009 and 2012 (Figure 2, Tables B2, B3). Temporal patterns of forest loss for buffer areas within 5 km of plantations (both certified and non-certified) were similar to non-certified plantations. Given the larger extent of non-certified plantations, mean annual forest losses differed by more than order of magnitude between certified and non-certified plantations (20,610 ha yr^{-1} and 194,070 ha yr^{-1}, respectively).

Although the use of fire for forest conversion is prohibited in Indonesia, satellite data suggest that one quarter of forest clearing in both certified and non-certified plantations involved fire (Table 1). For certified plantations in Indonesia, the proportion of fire-driven deforestation in both lowland and peat forests declined sharply following the cut-off date for new deforestation (Nov. 2005) but before the first RSPO certificates were issued (Fig. 2), from 37% during 2002-2005 to 19% in 2006-2008, and only 8% of all forest loss was identified as fire-driven deforestation after the first certificates were issued (2009-2014, Tables B2, B3). The proportion of fire-driven deforestation in non-certified plantations also declined over time, but not as rapidly as in certified plantations, especially in peat areas. Fire-driven forest losses accounted for 14% of total forest loss in non-certified and buffer areas from 2009-2014 (Table B2), but 34% of peat forest loss was identified as

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fire-driven deforestation (Table B3). Notably, the proportion of fire-driven deforestation in El Niño years (2002, 2006, 2009) was similar to or lower than non-El Niño years (e.g., 2003, 2007, 2010) for all three management types—certified plantations, non-certified plantations, and buffer areas.

However, certification did not halt forest conversion altogether. In Indonesia, forest loss continued within certified plantations following the start of RSPO certification efforts, including fires for forest conversion, leading to an additional 8% loss of remaining forest cover between 2009-2014 (Fig. 2, Tables B2, B3). Lower rates of forest loss on certified plantations are consistent with RSPO restrictions on clearing HCV forest areas and other lands deemed unsuitable for palm oil production. Declining rates of forest loss after 2009 may also reflect limited remaining forest cover on certified plantations by 2014 (15%; Fig. 2), leading to smaller clearing sizes that are more difficult to assess with remote sensing data on forest loss and fire activity (Fig. 3). In contrast, the contribution from larger clearing sizes increased over time in non-certified plantations and remained stable for buffer areas.

Patterns of fire-driven forest loss in certified plantations differed across Indonesia, Malaysia, and Papua New Guinea (Fig. 4). Overall forest loss rates were higher in Indonesia than Malaysia and Papua New Guinea (Table B1). However, large forest clearing events were more common on certified plantations in Malaysia and Papua New Guinea, with more than two-thirds of forest loss in patches >10 ha (Fig. A2). Annual forest loss rates in Malaysia remained high following certification, with little change from pre-certification patterns (Fig. 4, Tables B4, B5). In Malaysia, oil palm expansion in certified plantations rarely involved fire, and only 5% of total forest loss was identified as fire-driven deforestation (Tables B4, B5). Fire detections associated with forest loss declined in all three countries following the start of certification in 2008-2009. In Malaysia and Papua New Guinea, plantations with RSPO certificates had little fire-driven deforestation and few total fire detections for land management (Tables B4 – B6).

Certification decoupled fire detections from ENSO-driven variability in fire risk in Indonesia. Interannual variability in Indonesian fire activity is largely governed by the timing and magnitude of El Niño events (Fig. A1; Chen et al., 2016). Prior to 2009, interannual variability in fire detections was similar for certified plantations, non-certified plantations, and buffer areas in Indonesia (Fig. 5). Mean fire rates across land management classes were also consistent during El Niño events in 2002, 2004, and 2006, with important contributions from fire-driven deforestation to total fire detections in these years. Following certification, fire activity declined in certified plantations in all years, with 75% and 66% fewer fires km^{-2} than non-certified plantations during the 2009 and 2015 El Niño events, respectively (Figure 5, Table B6). Monthly fire counts confirmed the reduction in fire activity within certified plantations during peak burning months (August, September, October) of the 2009 and 2015 El Niño events (Fig. A3). Evidence for reduced fire activity in certified plantations highlights the potential for management of fire risk within oil palm plantations, even during strong El Niño drought conditions.

Attribution of fire activity is a critical component of satellite-based monitoring for environmental compliance. Higher resolution active fire data from VIIRS (375 m) and Landsat 8/OLI (30 m) confirmed the relative decline in fire activity on certified plantations compared to non-certified plantations and buffer areas in both 2014 and 2015 (Fig. 6). The

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VIIRS 375 m fire data provided a more complete characterization of the fire perimeter than MODIS on a daily basis. Although less frequent, Landsat 8 coverage every 16 days captured the precise location of active fire fronts, small fires, and persistent smouldering in peat areas that may last for many days (Fig. 6 and Fig. A4). High-resolution fire data offer improved understanding of fire use for deforestation and agricultural management, with detections that can be more definitively attributed to specific actors in support of monitoring, reporting, and verification.

4 Discussion

Following the issuance of the first RSPO certificates in 2009, certified oil palm plantations in Indonesia had lower fire-driven deforestation and total fire activity than non-certified plantations, including during El Niño events. These reductions point to the potential for RSPO to contribute to REDD+ and to decrease fire ignitions during drought conditions. Our findings of lower fire activity on certified plantations for both deforestation and land management during the 2009 and 2015 El Niño events contradicts earlier work by Cattau et al. (2015) showing higher fire activity on a small subset certified plantations, possibly due to a larger sample size of certified plantations in our study (N=154 compared to 28, with only 4 plantations on peat). However, certification did not halt forest losses or fire activity altogether, and rates of forest loss actually increased following the cut-off date for new deforestation but before the first RSPO certificates were issued. In addition, certified plantations currently account for a small fraction of total oil palm leases (e.g., 13% in Indonesia); non-certified plantations maintained higher rates of fire-driven deforestation and fire activity in recent years, including the 2015 El Niño. The opportunity exists, therefore, to enhance the environmental benefits of RSPO certification through expansion of certified plantations and strengthening of certification standards, including the use of satellite monitoring of fire activity and forest loss.

Our study confirmed the pervasive use of fire for forest conversion to oil palm in Indonesia, with one quarter of forest loss identified as fire-driven deforestation. Fire-driven deforestation was less common on certified plantations in Malaysia and Papua New Guinea, and fire use for forest conversion declined to near zero after the start of certification in 2008-2009 in these countries. The long-term records of Landsat forest loss and MODIS fire detections provide robust evidence of changing fire use for land management in certified oil palm plantations.

Several factors may account for the reduction in fire activity on certified plantations following certification. First, certification may reduce fire-driven deforestation by directly influencing land management practices. Collectively, all certified plantations in Indonesia, Malaysia, and Papua New Guinea showed declines in fire-driven forest losses after 2009. Second, the observed decline in fire activity may indicate an end of the expansion process rather than a change in fire-driven deforestation. Remaining forest cover was only 8-15% on certified plantations in Malaysia and Indonesia; remaining forest areas may not be suitable for oil palm or accessible based on RSPO restrictions. Similarly, a reduction in overall fire activity may be less important for GHG emissions than a reduction in peat fires (e.g., van der Werf et al., 2008; Cattau et al., 2016; Field et al., 2016). Regardless, the potential exists for RSPO to promote fire-free management of plantations to protect high-

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value tree crops and remaining carbon stocks in forests and peatlands. Large labor forces needed for oil palm production (Lambin et al., 2013) may aid regional fire suppression efforts, allowing established plantations to maintain lower fire activity in and around plantations during El Niño years.

The proportion of fire-driven deforestation on oil palm plantations in Indonesia (~25%) was similar to the estimate of combustion losses in bookkeeping models (30-40%; Houghton and Hackler, 1999), but fire use was much lower in Malaysia and Papua New Guinea. However, our study only confirms the coincident timing and locations of fires and forest losses, not the combustion completeness of fires for forest conversion. Removal of forest vegetation is critical to establish an oil palm plantation, but combustion completeness may be lower for these fires, given higher fuel moisture and less need for complete combustion of aboveground biomass than for expansion of row crop agriculture (Morton et al., 2008). Fuel moisture also has a substantial influence on trace gas emissions from fire, including smouldering fires in peatlands (Miettinen et al., 2012; Page and Hooijer, 2016). By combining active fire detections with satellite observations of trace gas emissions, it may be possible to characterize regional GHG emissions directly associated with fires on oil palm plantations. Complementary data on trace gas emissions may also compensate for missing satellite fire detections. The estimated fraction of fire-driven deforestation for different land management categories in this study is likely conservative because satellite platforms do not detect all fires. Satellite sensors may not sample at the peak of diurnal fire activity (Giglio et al., 2000), and cloud obscuration (Giglio et al., 2003) and orbital coverage (Schroeder et al., 2005) reduce the probability of fire detections, particularly for low-latitude regions with persistent cloud cover such as Southeast Asia. New satellite products partially overcome these limitations through improvements in orbital coverage and spatial resolution (Schroeder et al., 2014), especially for detection of small and low-intensity fires in deforestation or peatland areas (Schroeder et al., 2015; Elvidge et al., 2015).

Aligning certification criteria with existing satellite monitoring capabilities could improve the transparency, accountability, and impact of RSPO and other certification efforts. RSPO certification prohibits specific categories of forest clearing that cannot be readily distinguished using satellite data. For example, total forest loss can be identified using freely available satellite data products, but HCV or primary forest types cannot be confirmed with Landsat or MODIS data. Changing RSPO criteria to more closely match existing satellite data products on forest cover and forest loss would enable more rigorous monitoring of environmental compliance. Our study identified forest loss on plantations seeking certification after the cut-off date set by RSPO, but observations of forest loss do not confirm non-compliance with the Principles & Criteria of certification because HCV and primary forest areas cannot be confirmed using satellite data. Alternatively, public databases of set-aside areas on certified plantations (e.g., stream buffers, areas deemed unsuitable for production, or HCV) could improve transparency and support monitoring efforts without the need to derive forest conditions directly from satellite data. New, higher resolution active fire data also complement the time series of MODIS active fire observations. Landsat and VIIRS active fire data offer sufficient spatial detail to unambiguously attribute fire activity to specific land owners—an important step forward in satellite monitoring by governments, non-governmental organizations, or certification bodies such as RSPO. Fire suppression is important to safeguard carbon stocks in peatlands, and Landsat resolution is particularly

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beneficial for early detection of new wildfires and to identify small, smouldering fires in peat areas (Schroeder et al., 2015; Elvidge et al., 2015) that may persist for weeks and exacerbate GHG emissions and regional air quality during drought events.

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By 2020, Indonesia has pledged to double its palm oil production (Maulia, 2010), and expanding production threatens remaining rainforest and peatland areas. Certification offers a path for low-carbon development of additional oil palm production, provided that certification standards are consistent with capabilities for routine satellite monitoring. RSPO certification has reduced but not eliminated forest loss and fire use on certified plantations. To realize the full potential of certification, requirements for RSPO certification must be updated to align environmental goals with objective measures of compliance, including industry commitments to a goal of zero deforestation. Such transparency would also provide more direct insight into the key mechanisms through which agricultural intensification and expansion contribute to feedbacks in the Earth system.

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Acknowledgements

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Appendices

Appendix A Figures

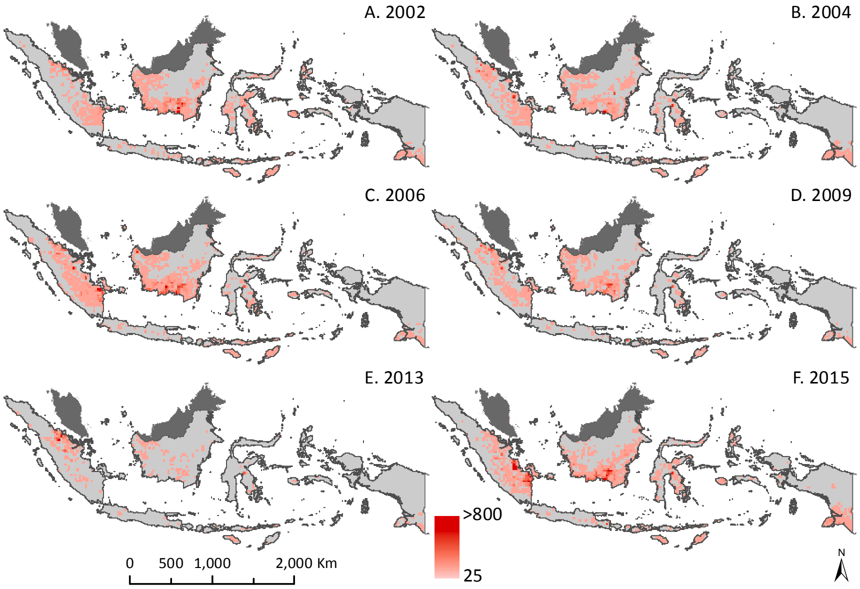

Figure A1: Density of MODIS active fire detections in Indonesia during El Niño years (A-D, F) and the June 2013 drought (E), when fires from Sumatra impacted air quality in Singapore (Gaveau et al., 2014). The spatial distribution of fire activity was consistent during El Niño years, although fire densities were highest in 2006 and 2015. Maps show annual totals of Terra and Aqua MODIS fire detections at 0.25° resolution.

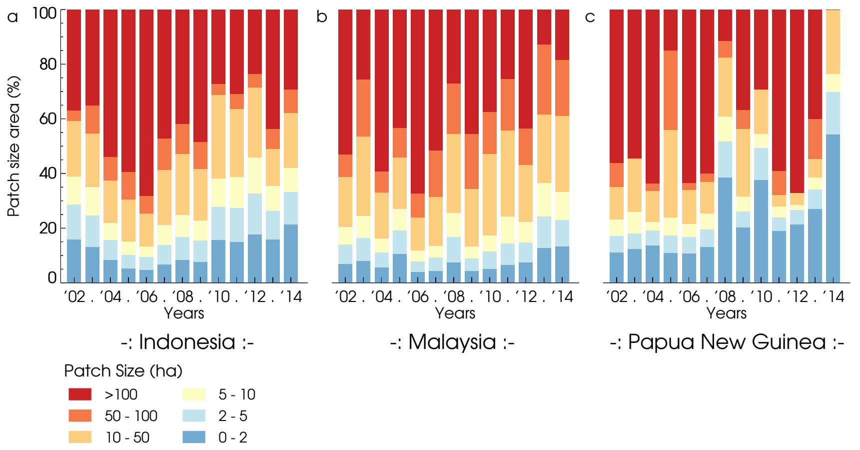

Figure A2: Forest loss patch size distribution in the RSPO Certified plantations of a) Indonesia, b) Malaysia, and c) Papua New Guinea. Patch sizes were assessed at the plantation level and summarized annually based on the proportion of total forest loss in each size class during 2002-2014.

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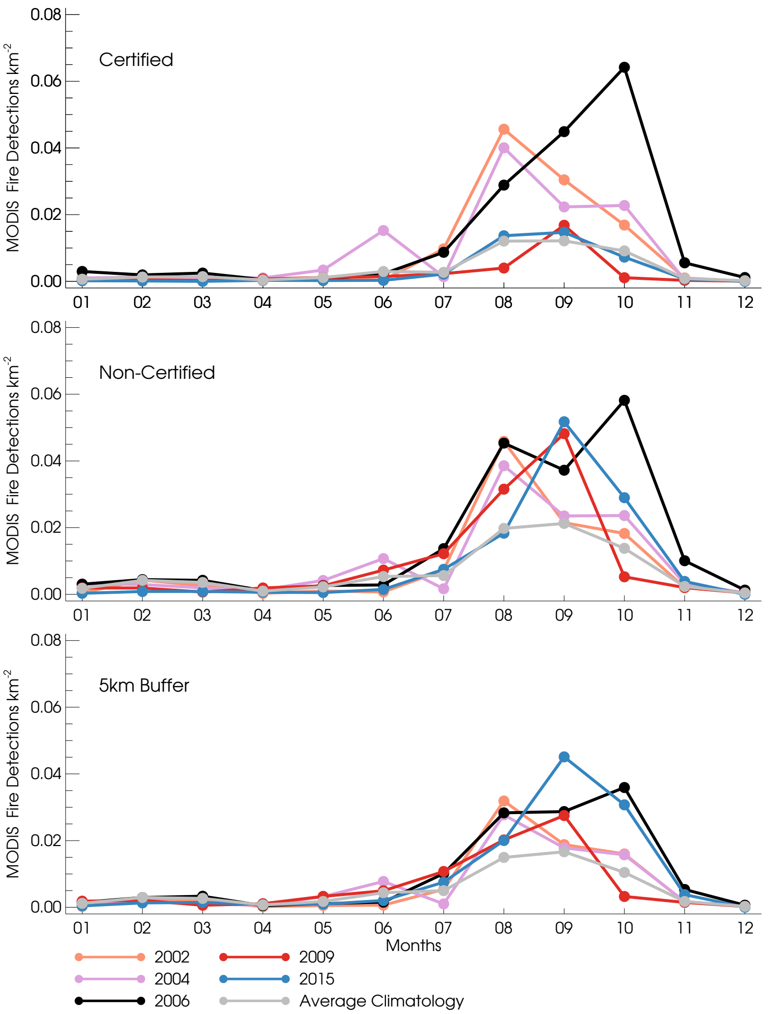

Figure A3: Monthly density of MODIS active fire detections (Terra and Aqua, combined) for certified plantations, non-certified plantations, and a 5-km buffer region surrounding plantations in Indonesia during El Niño years. A climatology of average monthly fire detections from all years (2001-2015) is shown in grey. 5

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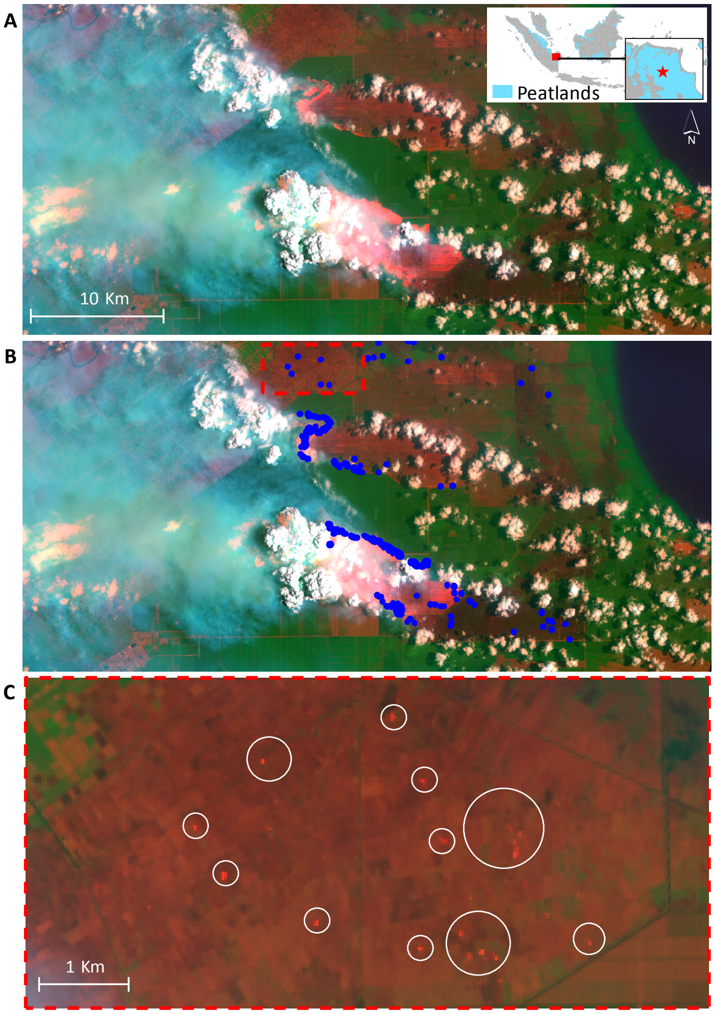

Figure A4: Landsat 8 active fire detections captured active fire fronts (B) and residual smouldering fires (C) in peatland areas of southern Sumatra on Sep. 30, 2015. White circles in panel C indicate smouldering for a subset of the image in panel B (dashed red outline). The regular grid of peatland drainage canals is visible in all panels.

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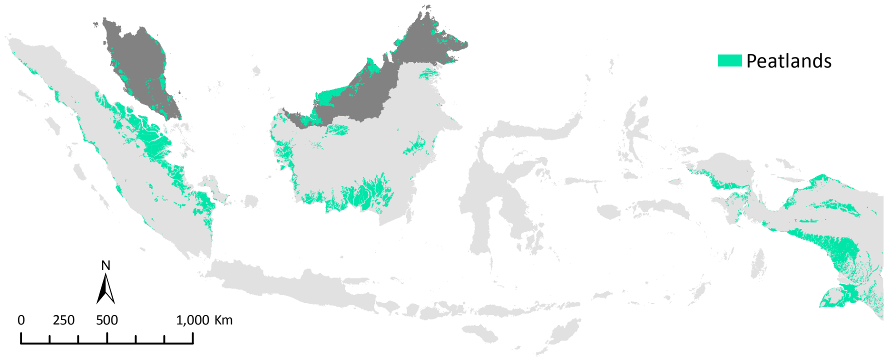

Figure A5: Extent of peatland in Indonesia and Malaysia (Wahyunto et al., 2003; 2004;2006 and WI, 2016).

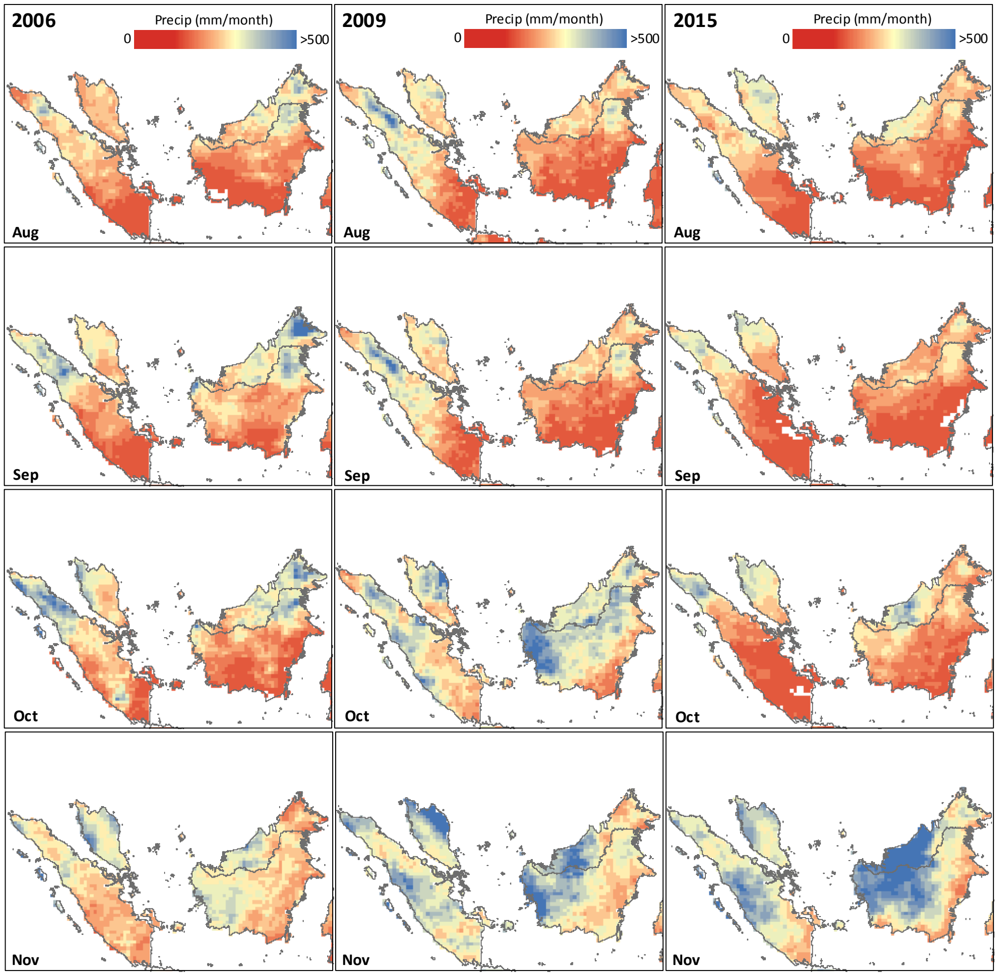

Figure A6: Monthly precipitation patterns for Indonesia and Malaysia from Tropical Rainfall Measuring Mission (TRMM) at 0.25° resolution for months with peak fire activity during the 2006, 2009, and 2015 El Niño events.

Appendix B Tables

Table B1: Total and fire-driven forest loss for oil palm expansion in certified plantations in Indonesia, Malaysia, and Papua New Guinea during 2002-2014. See Tables B2 – B5 for annual estimates of total forest loss, fire-driven forest loss, and the proportion of forest losses on plantations after the receipt of RSPO certification. All areas are given in hectares (ha).

	Lease area (ha)	Planted palm by 2010[a] (ha)	Forest loss (ha)	Peat Forest loss (ha)	Fire-driven loss[b] (ha)
Indonesia (IDN)	1,652,644	1,212,669	267,931	61,750	85,524 (26%)
Malaysia (MYS)	1,113,686	877,629	121,958	5,931	5,925 (5%)
Papua New Guinea (PNG)	174,439	94,001	21,491	-	3,860 (18%)

[a] Forest loss outside of peat areas

[b] Combined (peat and non-peat) forest loss related to fire

Table B2: Total and fire-driven forest loss for oil palm expansion in Indonesia from 2002-2014 within the certified and non-certified plantations. The percentage of total forest loss on plantations with RSPO certification is shown beginning in 2009. Totals exclude peat forest loss (see Table B3).

Year	Certified				Non-Certified		Buffer 5km	
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Fire-driven loss (ha)	Total loss (ha)	Fire-driven loss (ha)
2002	12,646	_	4,961	_	86,179	21,890	184,140	29,713
2003	7,043		2,552		53,578	18,693	104,882	23,135
2004	32,885		12,587		158,904	62,232	288,634	71,538
2005	33,795		9,170		140,345	42,260	244,178	56,281
2006	54,313		12,023		224,249	85,081	320,690	88,869
2007	34,218		6,905		203,990	61,875	303,782	67,606
2008	27,376		876		252,538	31,337	355,449	47,793
2009	29,229	(1)	2,543	(0)	335,246	62,356	446,635	79,842
2010	6,267	(8)	306	(0)	120,598	14,330	228,111	28,634
2011	7,105	(23)	308	(42)	240,864	22,776	316,644	34,771
2012	9,163	(25)	495	(25)	334,453	45,787	512,886	80,585

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2013	6,628	(50)	480	(82)	176,080	21,815	245,738	32,635
2014	7,264	(82)	774	(96)	195,885	31,298	302,012	48,848

Table B3: Total and fire-driven peat forest loss for oil palm expansion in Indonesia from 2002-2014 within certified and non-certified plantations. The percentage of total peat forest loss on plantations with RSPO certification is shown beginning in 2009, the year plantations in Indonesia were first granted RSPO certificates. See Table B2 for lowland forest loss on mineral soils.

Year	Certified				Non-Certified		Buffer 5km	
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Fire-driven loss (ha)	Total loss (ha)	Fire-driven loss (ha)
2002	3,408		452		26,271	13,496	36,719	14,116
2003	1,696		1,007		17,486	10,393	20,140	10,307
2004	6,555		3,789		47,330	23,756	71,975	30,891
2005	7,375		4,514		56,080	29,196	91,955	45,933
2006	18,119		4,938		45,606	28,978	60,686	31,992
2007	9,622		2,741		63,461	32,638	99,661	47,172
2008	4,888		350		60,468	13,057	65,747	16,117
2009	6,632	(0)	569	(0)	113,140	44,731	95,858	39,048
2010	514	(3)	121	(0)	38,743	11,717	70,823	23,902
2011	1,429	(55)	208	(89)	62,348	15,796	71,104	20,570
2012	584	(64)	80	(90)	100,402	30,024	120,737	46,583
2013	274	(55)	19	(93)	50,290	11,431	52,496	18,749
2014	654	(83)	201	(96)	60,400	23,404	79,305	38,035

Table B4: Total and fire-driven forest loss for oil palm expansion in certified plantations in Malaysia and Papua New Guinea during 2002-2014. All areas are given in hectares (ha), and totals exclude peat forest loss (see Table B5). The percentage of total forest loss on plantations with RSPO certification is shown beginning in 2008.

	Malaysia				Papua New Guinea			
Year	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)
2002	14,870		912		3,959		1,244	
2003	6,563		791		1,645		301	
2004	13,522		1,912		3,279		721	
2005	6,410		506		1,242		252	
2006	12,312		465		2,893		718	
2007	12,045		15		2,099		479	
2008	7,381	(2)	91	(0)	1,188	(34)	116	(7)
2009	15,467	(8)	69	(0)	938	(71)	3	(0)
2010	10,378	(19)	155	(8)	716	(85)	14	(96)
2011	8,222	(35)	120	(65)	1,065	(85)	4	(98)
2012	7,432	(48)	235	(63)	1,235	(79)	3	(77)
2013	3,261	(50)	85	(78)	756	(100)	0	(100)
2014	4,096	(82)	114	(81)	477	(100)	3	(100)

Table B5: Total and fire-driven peat forest loss for oil palm expansion in certified plantations in Malaysia during 2002-2014. All areas are given in hectares (ha). The percentage of total peat forest loss on plantations with RSPO certification is shown beginning in 2008. See Table B4 for lowland forest loss on mineral soils.

Year	Malaysia			
	Total loss (ha)	Post-Certification loss (%)	Fire-driven loss (ha)	Post-Certification loss (%)
2002	303		2	
2003	97		26	
2004	272		0	
2005	388		32	
2006	210		12	
2007	238		0	
2008	300	(5)	0	(0)
2009	780	(37)	81	(0)
2010	1,146	(33)	12	(1)
2011	559	(35)	15	(95)
2012	1,243	(48)	1	(0)
2013	207	(58)	8	(100)
2014	187	(91)	7	(100)

Table B6: Total MODIS fire detections for certified plantations in Indonesia, Malaysia, and Papua New Guinea. The percentage of fire detections on plantations with RSPO certification is shown for 2008 – 2015.

	Indonesia		Malaysia		Papua New Guinea	
Year	Total fire detections	Post-Certification fire detection (%)	Total fire detections	Post-Certification fire detections (%)	Total fire detections	Post-Certification fire detections (%)
2001	169		124		37	
2002	1782		87		130	
2003	716		71		64	
2004	1821		87		130	
2005	1008		128		39	
2006	2712		17		83	
2007	197		12		61	
2008	87		9	(0)	43	(7)
2009	483	(0)	22	(0)	31	(0)
2010	72	(8)	18	(28)	44	(95)
2011	196	(29)	12	(50)	18	(67)
2012	191	(39)	21	(33)	44	(84)
2013	128	(55)	11	(55)	54	(100)
2014	361	(73)	35	(69)	52	(100)
2015	656	(100)	26	(100)	136	(100)

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Figures

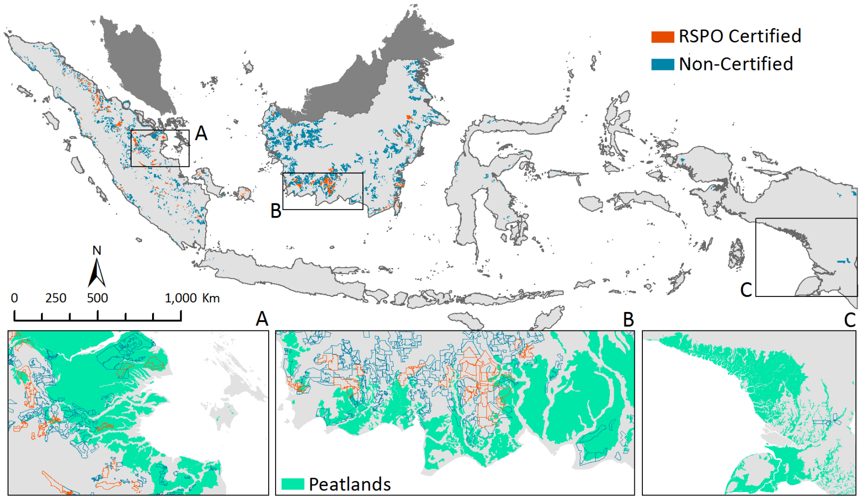

Figure 1: Extent of RSPO certified (red) and non-certified (blue) oil palm plantations in Indonesia. Regional subsets highlight plantations boundaries on peatlands (green) in lowlands of Sumatra (A), Kalimantan (B), and Papua (C).

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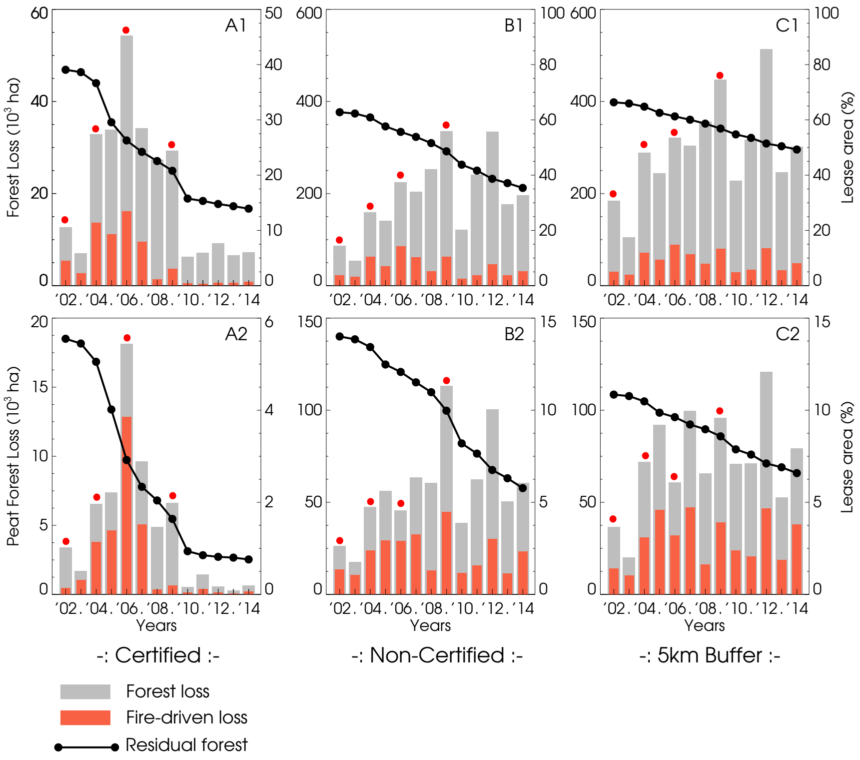

Figure 2: Forest loss within the boundaries of A) Certified plantations, B) Non-Certified plantations, and C) 5km Buffer region surrounding certified and non-certified plantations in Indonesia from 2002-2014. A1-C1) Forest loss (grey) and fire-driven forest loss (orange); A2-C2) Peat forest loss (grey) and fire-driven peat forest loss (orange). Solid black lines indicate residual forest cover as a percentage of management areas. Annual estimates of total forest loss and fire-driven forest loss are summarized in Tables B2 and B3, including the proportion of forest losses on plantations after the receipt of RSPO certification. Orange dots indicate El Niño years.

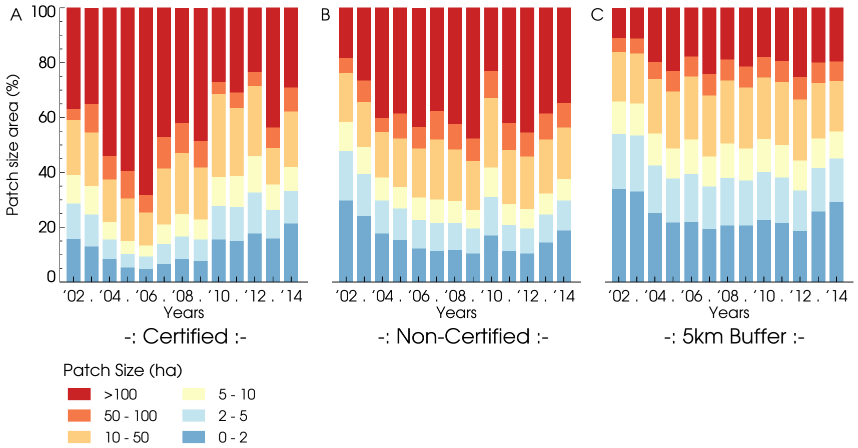

Figure 3: Forest loss patch size distribution in Indonesia within the boundaries of A) RSPO Certified plantations, B) Non-Certified plantations, and C) 5km Buffer region. Patch sizes were assessed at the plantation level and summarized annually based on the proportion of total forest losses in each size category during 2002-2014.

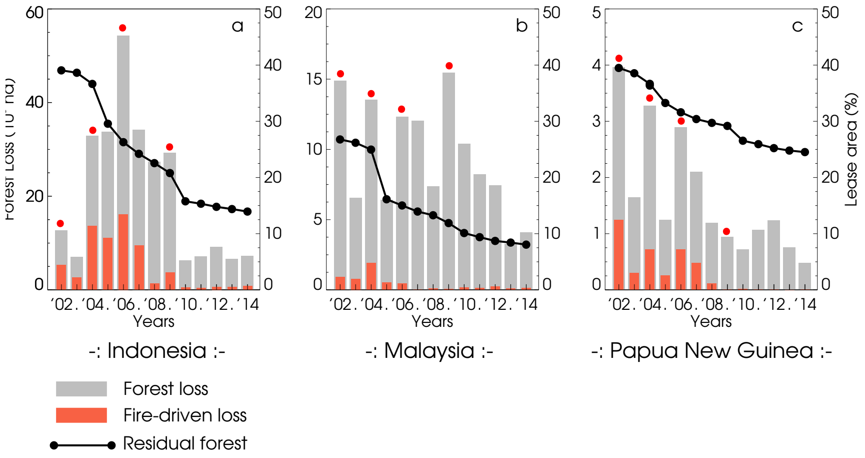

Figure 4: Total forest loss (grey) and fire-driven forest loss (orange) in certified plantations in a) Indonesia, b) Malaysia, and c) Papua New Guinea. Forest loss was estimated outside of planted palm (Carlson et al., 2013; Gunarso et al., 2013). Black lines indicate remaining forest area as a fraction of the total lease area of certified plantations in each country. Annual estimates of total forest loss and fire-driven forest loss for certified plantations are summarized in Tables B2 - B5, including the proportion of forest losses on plantations after the receipt of RSPO certification. Orange dots indicate El Niño years.

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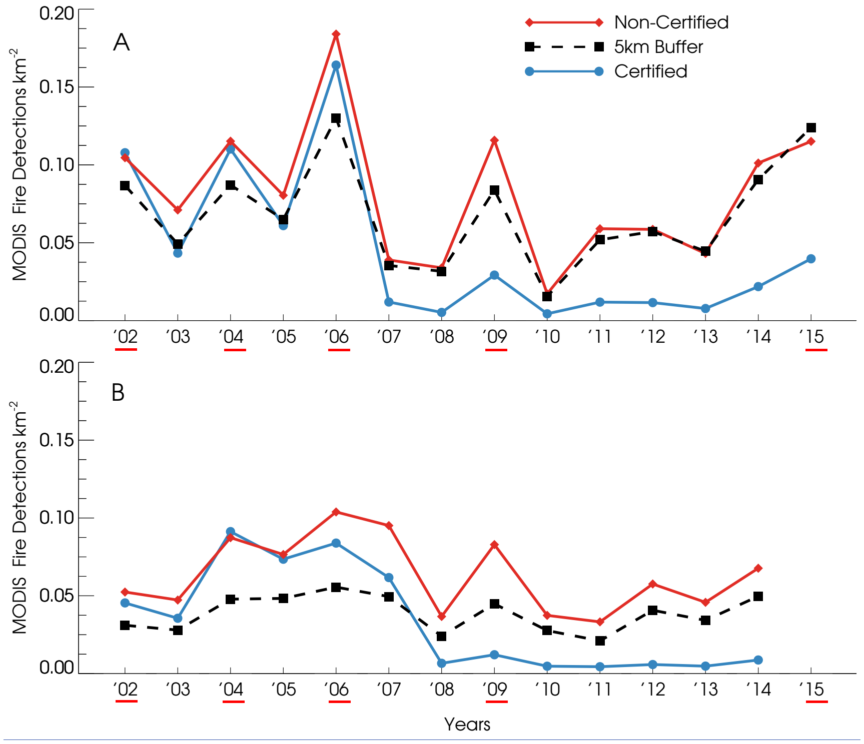

Figure 5: Density of MODIS active fire detections within certified plantations, non-certified plantations, and the 5-km buffer region around plantations in Indonesia from 2002-2014. A) Time series of all MODIS active fire detections; B) Time series of MODIS active fire detections associated with fire-driven deforestation. El Niño years are underlined in red. Table B6 provides annual estimates of fire counts on certified and non-certified plantations, including the proportion of fire detections on plantations 5 **after the receipt of RSPO certification.**

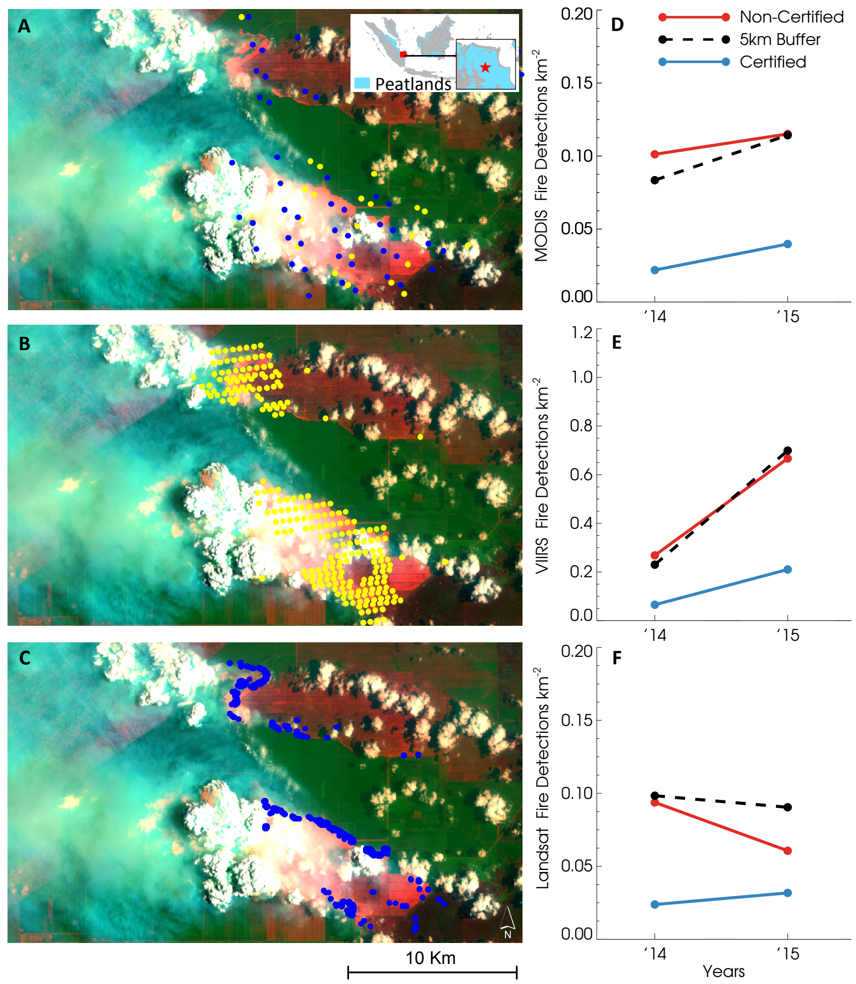

Figure 6: High-resolution active fire detections confirm lower fire activity in certified plantations during the 2015 El Niño event. Map panels show active fire detections on Sep. 30, 2015 for peat fires in southern Sumatra from A) Terra (blue) and Aqua (yellow) MODIS (1 km), B) S-NPP/VIIRS (375m), and C) Landsat-8/OLI (30m). Background images in panels A-C are a false-color

composite of Landsat 8/OLI bands 7-5-3 from the same date (Path/Row: 124/62). Adjacent panels show total annual fire detections in 2014 and 2015 for certified plantations from D) MODIS, E) VIIRS, and F) Landsat 8/OLI.

Tables

Table 1: Total and fire-driven forest loss for oil palm expansion in Indonesia from 2002-2014 within certified and non-certified plantations. See Tables B2 and B3 for annual estimates of total forest loss, fire-driven forest loss, and the proportion of forest losses on plantations after the receipt of RSPO certification.

	Lease area (ha)	Planted palm by 2010 (ha)	Forest loss[a] (ha)	Peat Forest loss (ha)	Fire-driven loss[b] (ha)
RSPO Certified	1,652,644	1,212,669	267,931	61,750	85,524 (26%)
Non-Certified	11,266,875	3,416,302	2,522,909	742,025	810,346 (25%)
5km Buffer	25,092,975	2,931,778	3,853,782	937,206	1,073,664 (22%)

[a] Forest loss outside of peat areas

[b] Combined (peat and non-peat) forest loss related to fire

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